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MORGANTOWN ENERGY TECHNOLOGY CENTER

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Gas Stream Cleanup

Technology Status Report

Editors
M.C. Williams
R.C. Bedick

October 1988

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U. S. DEPARTMENT OF ENERGY
OFFICE OF FOSSIL ENERGY
MORGANTOWN ENERGY TECHNOLOGY CENTER
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1.0 INTRODUCTION

To realize the potential of emerging energy conversion systems that use coal, innovative approaches must be developed to manage the contaminants that are generated during the energy conversion process. Coal consists primarily of carbon compounds and varying amounts of minerals. When coal is used in emerging conversion systems to produce energy, it is burned and produces an exhaust gas, or it is gasified and produces a valuable fuel gas that can be further processed. Unfortunately, these exhaust and fuel gases contain contaminants that can degrade the system equipment or the environment. To prevent this degradation, the contaminants must be removed from the exhaust and fuel gases.

The objective of the Gas Stream Cleanup (GSC) Program at the U.S. Department of Energy's (DOE's) Morgantown Energy Technology Center (METC) is to develop contaminant control technology to separate out, or otherwise control, contaminants from the hot exhaust or fuel gases. The program's activity is mainly aimed at separating out contaminants at pressures greater than 5 atm and temperatures greater than 1,000°F. These elevated pressures and temperatures are associated with seven emerging systems: pressurized fluidized-bed combustion (PFBC), integrated gasification combined-cycle (IGCC), gasification/molten-carbonate fuel-cell (MCFC), gasification/solid-oxide fuel-cell (SOFC), direct coal-fueled turbine (DCFT), coal-fueled diesel (CFD), and mild gasification (MG). It is advantageous to conduct GSC separations under elevated temperatures and pressures because this minimizes the need for expensive heat-recovery equipment and avoids efficiency losses that are associated with fuel-gas quenching. In gasification systems, keeping the gas hot is beneficial since tars are not condensed, but rather are burned downstream in a combustor, adding heat to the system and reducing the problems associated with disposal and wastewater treatment. Since gasification system contaminants can be separated before combustion and expansion or cooling, the volume of gas that must be processed is reduced and the contaminant concentration is increased, resulting in increased separation efficiencies and smaller sized equipment.

The contaminants that are of major concern to the GSC program are sulfur and nitrogen compounds, particulates, alkali, halogens, ammonia, and trace contaminants. Sulfur, present at up to 5 weight-percent (wt-%) in coal, can be detrimental to the components in a new energy conversion system and is an environmental pollutant when oxidized to sulfur dioxide during combustion. Sulfur that is present as hydrogen sulfide in gasifier fuel gas degrades the performance of MCFCs. The effect that sulfur and other contaminants have on the SOFC is not expected to be as pronounced as it is for the MCFC. Since the operating temperature of the phosphoric acid fuel cell is 400°F, hot gas cleanup is not being considered. Particulates or particles play a significant role in erosion, corrosion, and deposition phenomena in all energy conversion systems. Alkali, such as sodium and potassium sulfates, hyroxides, and chlorides are present at up to 1 wt-% in coal. These alkali contaminants corrode the metals used in turbines that extract energy from hot gas streams in IGCC, PFBC, and DCFT systems. Halogens, such as hydrochloric acid, degrade the performance of MCFCs. Ammonia needs to be separated or decomposed to prevent the subsequent formation of nitrogen oxides (NO_x) downstream when the fuel gas is combusted. Trace contaminants, such as arsenic, lead, and selenium, present in coal degrade the performance of energy systems, such as MCFCs. These contaminants also harm the environment.

2.0 ORGANIZATIONAL BACKGROUND

The activities of GSC can be conveniently organized under the systems in which the contaminant control technology has been or plans to be implemented. Many of the activities are cross-cutting, since some systems have similar operating conditions, temperatures and pressures, and similar gas compositions. This makes GSC technology transferable from system to system. This Technology Status Report discusses each GSC activity in most detail under the system in which its development has proceeded most quickly. The potential for cross-cutting technology transfer is pointed out where appropriate.

3.0 SYSTEM DESCRIPTIONS

3.1 Introduction

The seven advanced energy-conversion systems presently served by GSC are described in the following sections. Each system involves coal combustion or gasification. The systems differ primarily in whether the coal is immediately combusted or is gasified and subsequently combusted or processed. Each system consists of two primary subsystems: the coal combustion or gasification subsystem and an end-use subsystem, such as a turbine or fuel cell. The developmental status of the primary subsystems is continually evolving. Improvements such as gasifier in-situ desulfurization and improved MCFC contaminant tolerances are contributing significantly to system integration. In addition to the gasification and combustion subsystems, the emerging systems consist of subsystems (GSC subsystems such as zinc ferrite reactors for H_2S removal, for example). GSC provides the contaminant control subsystems that are essential to system integration; these subsystems are the focus of this report.

3.2 Pressurized Fluidized-Bed Combustion System

A PFBC system is shown in Figure 1. Properly sized coal and sorbent (dolomite or limestone) are fed to the pyrolyzer and combustor. As the coal burns, the released sulfur compounds react with the sorbent to form a solid material that is removed at the bottom of the combustor along with the coal ash. Heat is removed from the combustor by in-bed heat exchangers that produce steam to drive a steam turbine. Combustion gases exit the combustor and are eventually expanded in a gas turbine to produce additional power. Performance goals for second generation systems are an efficiency approaching 45 percent

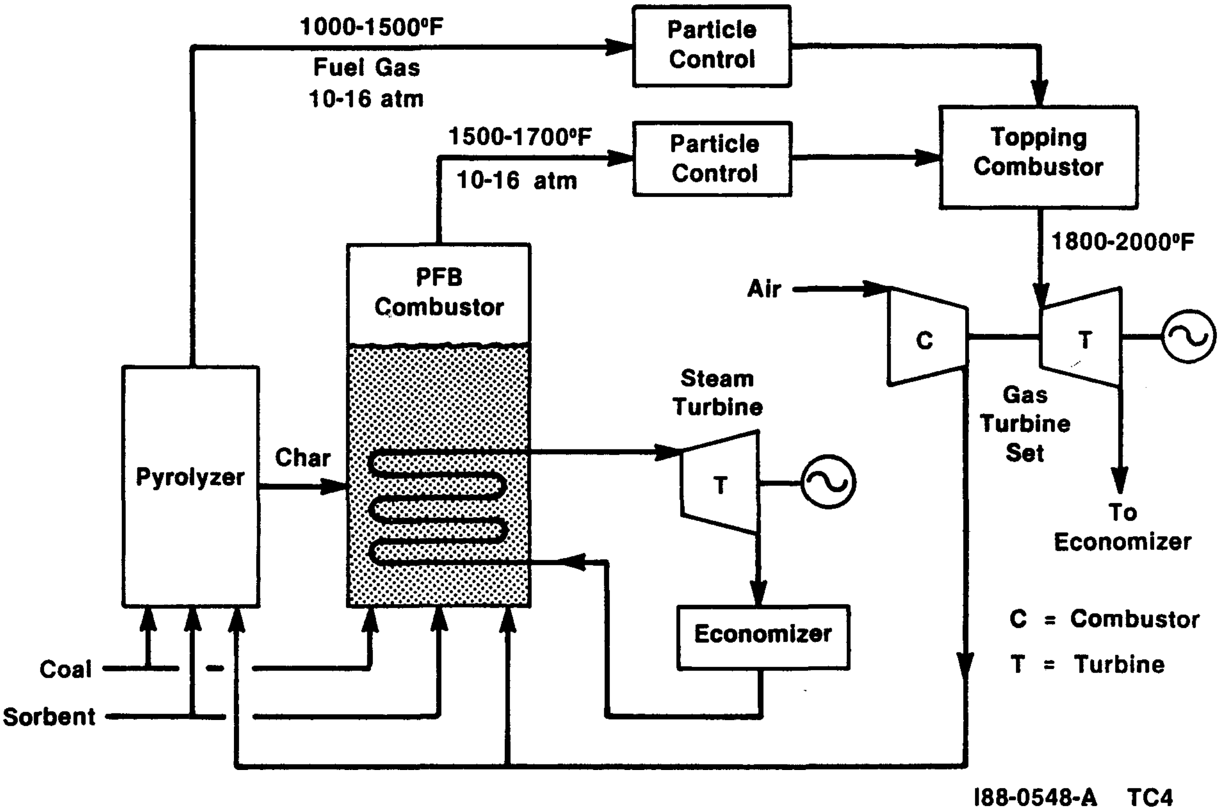

Figure 1. Second-Generation, Advanced-Cycle Pressurized Fluidized-Bed Combustor

and cost of electricity (COE) reductions of at least 20 percent below conventional pulverized coal boilers with flue gas desulfurization.

The second-generation (Figure 1) PFBC system needs high-temperature and high-pressure (HTHP) particle control to protect the turbine and to meet environmental requirements. It is expected that particles are the primary contaminant of concern. As shown in Figure 1, particles are removed from the fuel gas streams before they reach the topping combustor. Strategies such as in-pyrolyzer limestone addition and staged combustion are being developed to control sulfur dioxide (SO_2) and NO_x emissions, respectively.

3.3 Direct Coal-Fueled Turbine System

The DCFT system, which is shown in Figure 2, uses dry pulverized coal or a coal-water slurry as the fuel. The coal is burned directly in the combustor, and the gas is expanded in the turbine. In this system, the combustor is generally external to the turbine and in most systems contaminants of > 10 micrometers (μm) must be removed from the gases between the combustor and the turbine inlet. Depending on the specific system, contaminant removal needs to be accomplished at temperatures between 1,800 and 2,250°F and at

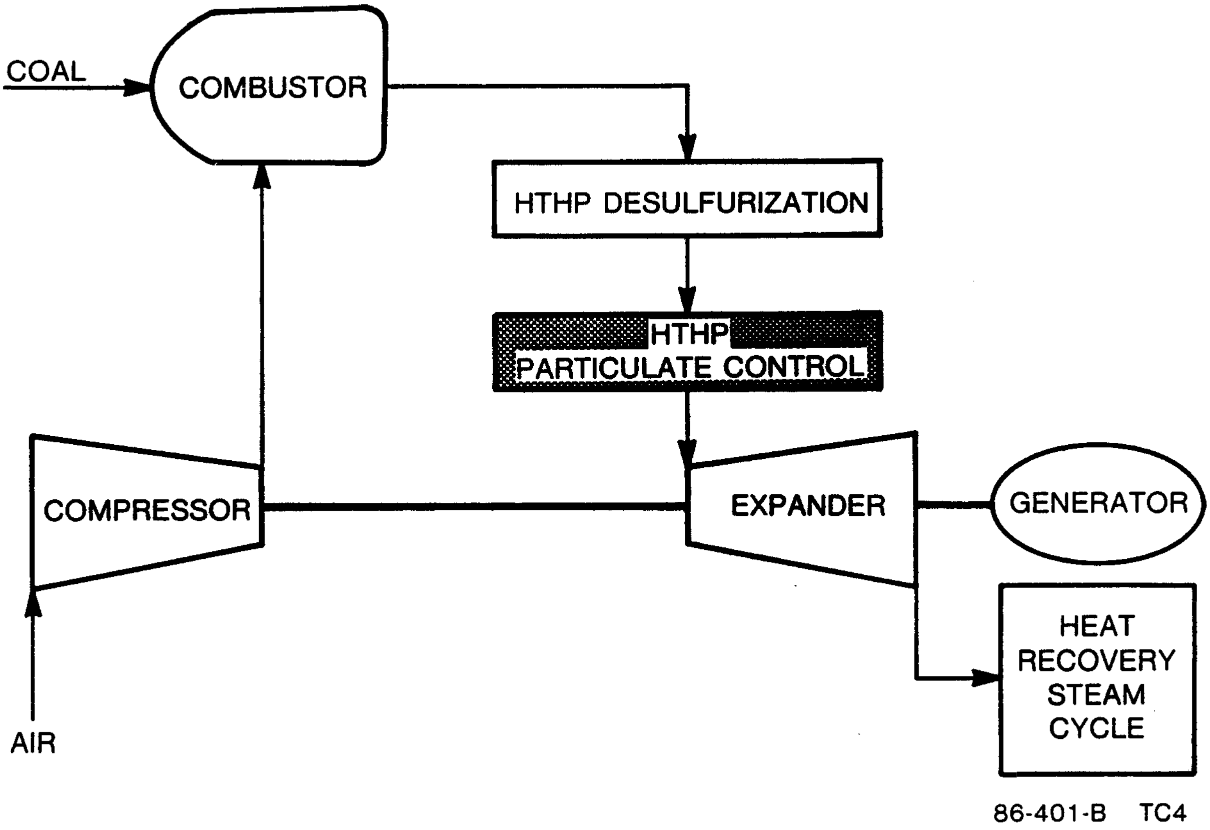

Figure 2. Simplified, Direct Coal-Fueled Turbine System

pressures from 120 to 500 pounds per square inch gauge (psig). Presently, it is believed that particles and sulfur compounds are the contaminants that represent the most significant control problem. The major advantages of a DCFT system are its simplicity and its potential for using a wide range of fuels. It is projected that total energy conversion efficiencies as high as 50 percent are possible.

3.4 Integrated Gasification Combined-Cycle System

Figure 3 shows the general arrangement of a simplified IGCC system. For power generation from coal, IGCC systems promise to be an efficient and economical route for modular power plants. Total energy conversion efficiencies for IGCC systems are projected to approach 50 percent. Gas turbines coupled with coal gasifiers can be implemented as modular power blocks into a total system. These modules can be shop fabricated and field assembled.

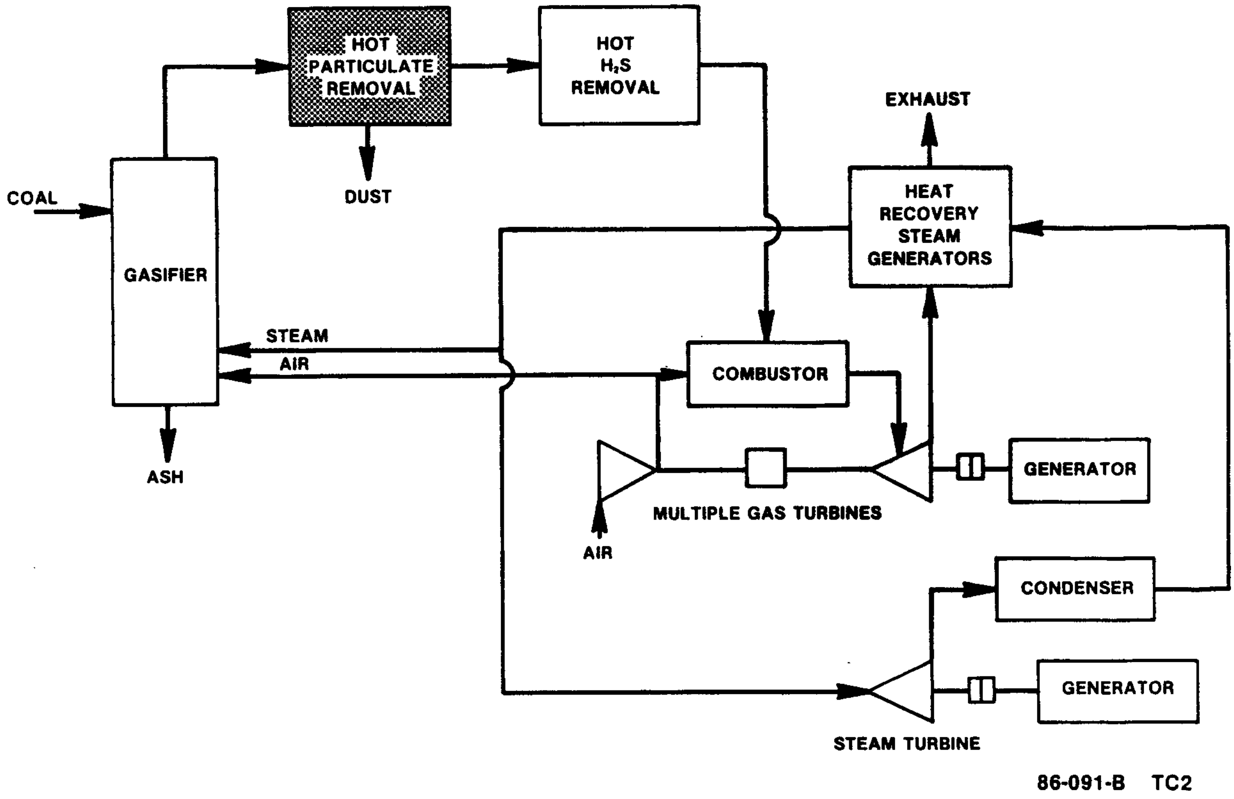

Figure 3. Simplified, Integrated Gasification Combined-Cycle System

In the IGCC system, the gasifier converts the coal into a gaseous fuel by reacting it with air and steam at a high temperature. To fully integrate the IGCC system, it is necessary to match the temperature and pressure of the gasifier and turbine. Various contaminant control subsystems must be integrated into the IGCC system in order to produce a fuel that does not contain intolerable levels of contaminants. To preserve system efficiency and reduce capital costs, particles and gaseous contaminants must be removed from the fuel gas before the gas is combusted and expanded through the gas turbine.

There are many configurations of IGCC systems that can use various types of gasifiers and can have different cleanup requirements. The fixed-bed gasifier can deliver a fuel gas at temperatures up to 1,000°F. The fluidized-bed gasifier can produce a fuel gas in the 1,200°F and higher range. Both gasifiers produce a fuel gas that can be desulfurized by the zinc ferrite process (after the gas undergoes partial cooling to 1,200°F, if needed). A calcium sorbent also can be added directly to both gasifiers to capture sulfur as it is released from the coal. Capture efficiencies have been shown to be as high as 90 percent in a fluidized-bed gasifier using a high-sulfur coal.

The entrained-flow gasifier system may provide efficiency and economy improvements if a higher temperature fuel gas (one that has not been quenched significantly) is used. The combination of high fuel feed temperatures and control of contaminants in order to simultaneously protect equipment and meet environmental emissions requirements is the primary problem in developing this system. Novel desulfurization sorbents that can operate effectively at 1,400°F and higher may be necessary to optimize system efficiency. The GSC activities that are aimed at those developments will be discussed in Section 4.

3.5 Gasification/Fuel Cell System

The two primary gasification/fuel cell systems that are under investigation are the MCFC (Figure 4) and SOFC systems (Figure 5). In an MCFC system, hydrogen and carbon monoxide in the fuel gas are used to produce electricity directly. A fuel cell consists of two electrodes, the cathode and the anode, separated by an electrolyte. Fuel gas from a coal gasifier is fed to the anode where it is oxidized, while an oxidant (air) is fed to the cathode, where it is reduced. Electrons liberated by the oxidation reaction at the anode are conducted through an outer circuit to the cathode for the reduction reaction; the electron flow through the outer circuit produces direct-current electricity. Contaminants must be removed from the fuel gas before it enters the fuel cell, primarily to prevent clogging of the gas passages in the anode and poisoning of the electrodes. Additional energy can be produced in the MCFC system by a heat recovery step that produces steam to run a steam turbine and to supply process heat. It is projected that total energy conversion efficiencies for a MCFC system can exceed 50 percent.

There are a number of possible system configurations for MCFC systems; the simplified system configuration is illustrated in Figure 4. In general, there are system tradeoffs among the operating conditions of the gasifier, GSC contaminant control subsystems, and the MCFC system. These tradeoffs include parameters such as temperature, pressure, and gas composition. The MCFC system operates at a temperature of 1,200°F; target pressures are 90 to 150 psig. However, the gasifier and GSC subsystems may operate most effectively at other conditions, so it is necessary to adjust the gas stream conditions and recover energy through heat exchangers and expanders.

In a SOFC system, the hydrogen and carbon monoxide in the gasifier fuel gas are used to generate electricity directly. There are a number of possible system configurations for SOFC systems. Again, there are generally system tradeoffs among the operating parameters of the gasifier, GSC subsystems, and the SOFC system. Operating parameters include temperature, pressure, and gas composition. The current SOFC system operates at a temperature of 1,800°F and a pressure of 14.7 pounds per square inch absolute (psia). The benefits and effects of operating at elevated pressure are being examined. In most cases the gasifier and cleanup units operate most effectively at temperatures and pressures that are different from those of the fuel cell; it is therefore necessary to adjust the gas stream conditions and recover energy through heat exchangers and expanders. The SOFC system is potentially very efficient: coal-to-bus-bar electrical efficiencies are expected to exceed 50 percent.

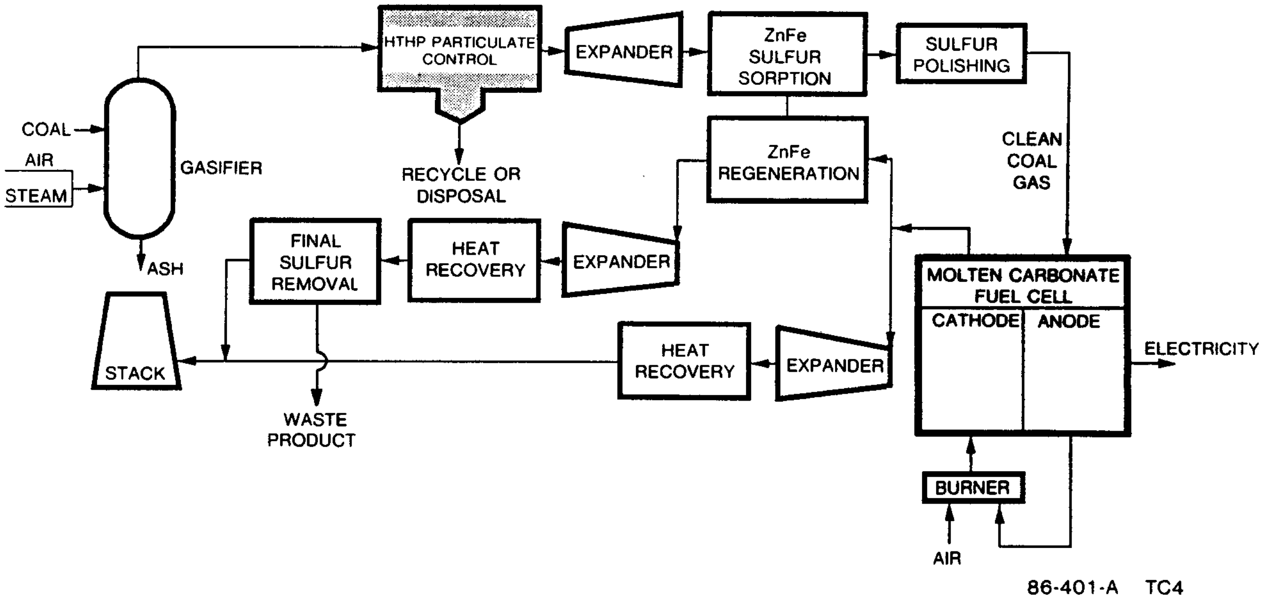

Figure 4. Gasifier/Molten-Carbonate Fuel-Cell System

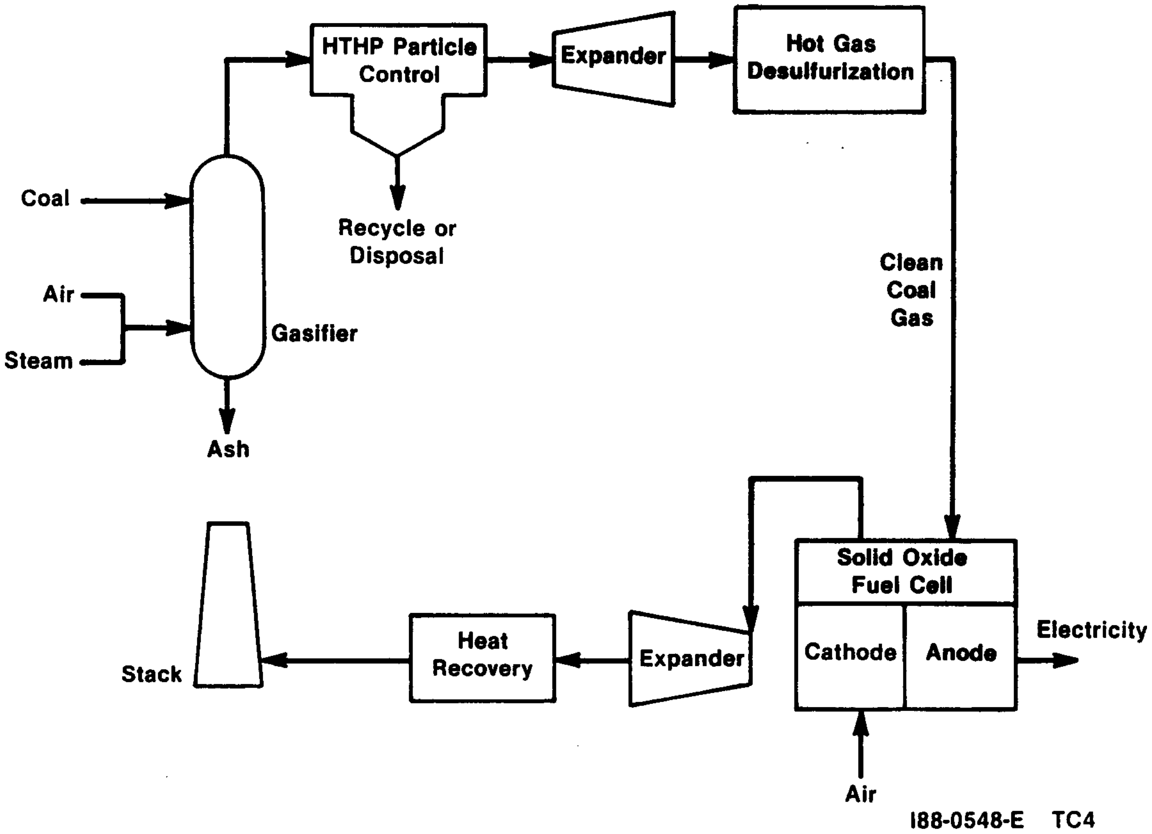

Figure 5. Gasifier/Solid-Oxide Fuel-Cell System

3.6 Coal-Fueled Diesel System

Operation of diesel engines with coal-based fuels offers a potential economic advantage by replacing conventional diesel fuel with a relatively low-cost fuel that is derived from coal. The coal-based fuels that are being considered for use in diesel engines include coal slurries, micronized coal, coal-derived liquids, and gaseous fuels. Diesel applications include small stationary power plants, industrial cogeneration applications, locomotive applications, and marine applications. Figure 6 depicts a conceptual CFD system. Strategies are being developed to control CFD emissions including soot, particulates, and sulfur and nitrogen oxides.

3.7 Mild Gasification System

MG systems generate multiple products by low-temperature treatment of coal (Figure 7). The products that are generated are characterized as coal-derived liquids, gases, and chars. These products are generated by applying advanced processing techniques, new catalysts, advanced treatment schemes, and novel methods for product upgrading. However, contaminants such as particles, sulfur and nitrogen compounds, alkalis, and trace elements detract from the usefulness of the generated products. Requirements for contaminant removal will likely be different for each type of MG process.

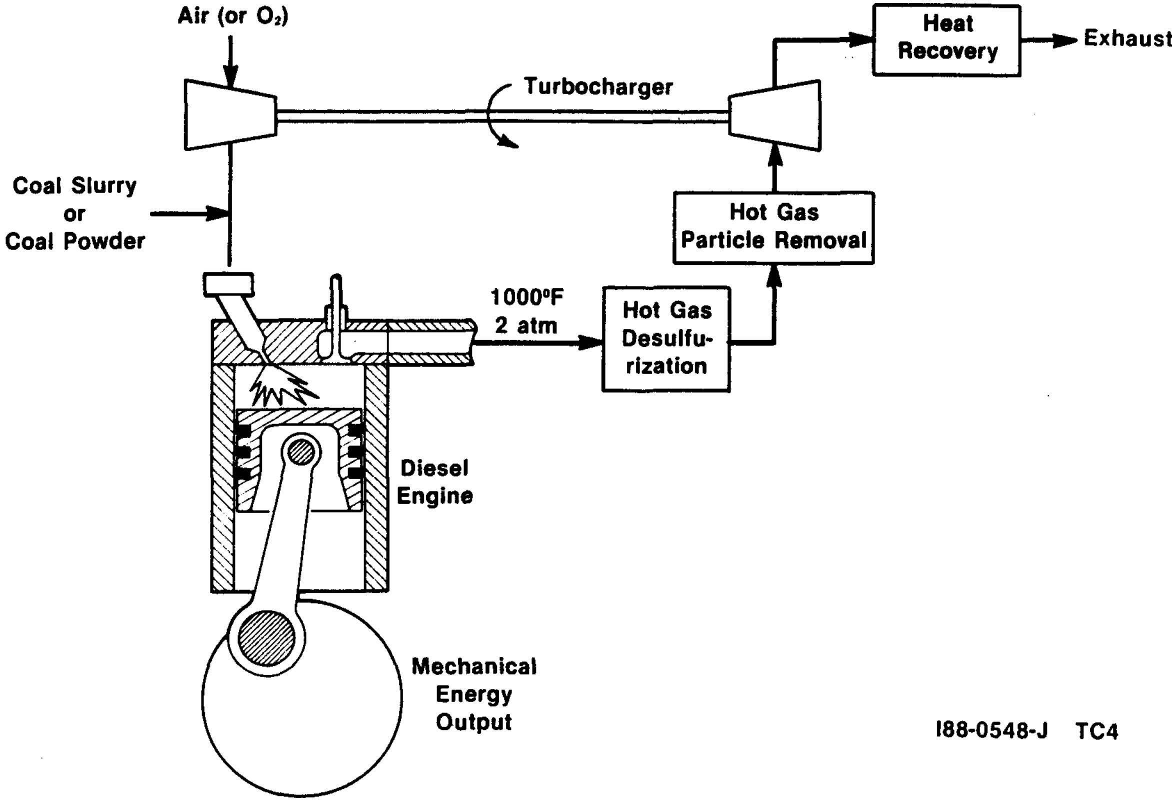

Figure 6. Conceptual Coal-Fueled Diesel System

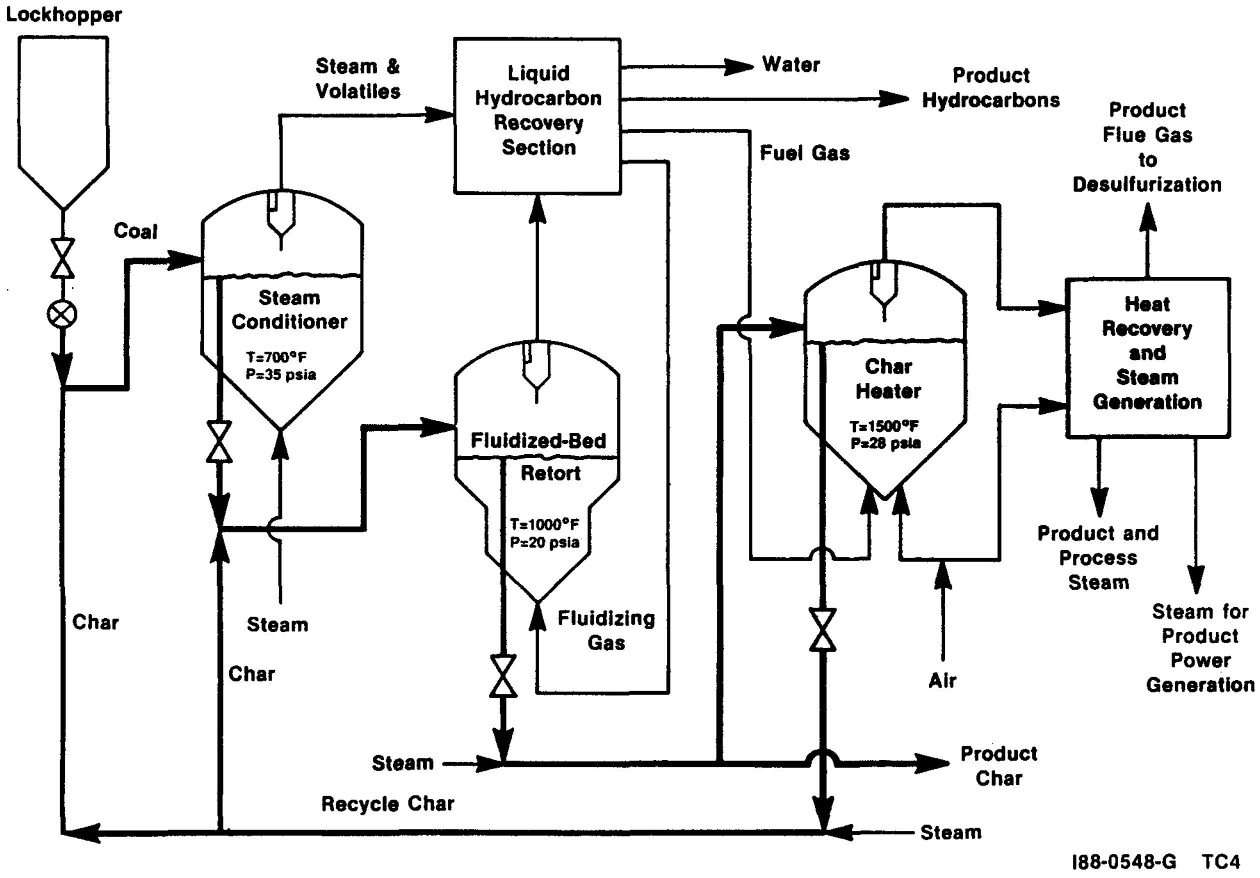

Figure 7. Conceptual Mild Gasification System

4.0 GAS STREAM CLEANUP FOR THE VARIOUS SYSTEMS

4.1 Introduction

The activities of the GSC program are presented in the system in which GSC contaminant control technologies are presently being tested. In time, the technology developed for one system may be transferred to other systems. Proof-of-concept (POC) integrated testing of the seven energy conversion systems is considered an essential step toward commercial development. In integrated testing, all the subsystems are tested together.

4.2 Gas Stream Cleanup for the Pressurized Fluidized-Bed Combustion System

The potential for hot gas cleanup to increase the overall efficiency of power systems is significant, and the overall cost-per-unit capacity for such systems is expected to diminish substantially relative to cold gas cleanup. The levels of contaminant removal for an optimized PFBC system are shown in Table 1.

In-bed desulfurization using calcium-based sorbents achieves the required sulfur removal goals that have been established to meet environmental considerations. However, there are still corrosive problems caused by other contaminants that are present in the process stream, particularly the alkali metals.

The best tool that is currently available for total alkali measurements is the METC fiber optic alkali monitor (FOAM) (Figure 8). It is based on a flame emission spectrometry technique that was developed at Ames National Laboratory and can detect total or vapor sodium and potassium at the parts-per-million by weight (ppmw) to the parts-per-billion by weight (ppbw) level. During 1987, characterization of operating PFBC systems was begun by Ames National Laboratory. The objective of this work is to ascertain what level of alkali is really present in PFBC exhausts in order to decide whether alkali control technology needs to be further developed. PFBC systems at Grimethorpe, Argonne National Laboratory (ANL), and New York University (NYU) were characterized in late 1987. Data analysis is still underway.

There are several proposed methods for separating vapor-phase alkali from a HTHP process stream. Work at developing alkali control technology is continuing at ANL. The objective is to evaluate the performance of activated bauxite to control vapor-phase alkali in PFBC systems. During the work, several serious problems have been encountered. A series of experiments has

Table 1. Conditions and Cleanup Goals for the Pressurized Fluidized-Bed Combustion System

Temperature (°F)	1,500-1,700
Pressure (psig)	100-240
Uncontrolled Particulate Loading (ppmw)[a]	1,000-20,000
Outlet Particulate Loading (ppmw)[b]	1 > 5 μm
Alkali	0.02 ppmw
Ammonia (nitrogen)	*
Halogen Compounds (HCl, etc.)	*
Sulfur	∆

[a] These are nominal loadings after one stage of cyclones; [b] At the outlet of the particulate control device; * Can be controlled without hot gas cleanup; ∆ Controlled with in-bed sorbents.

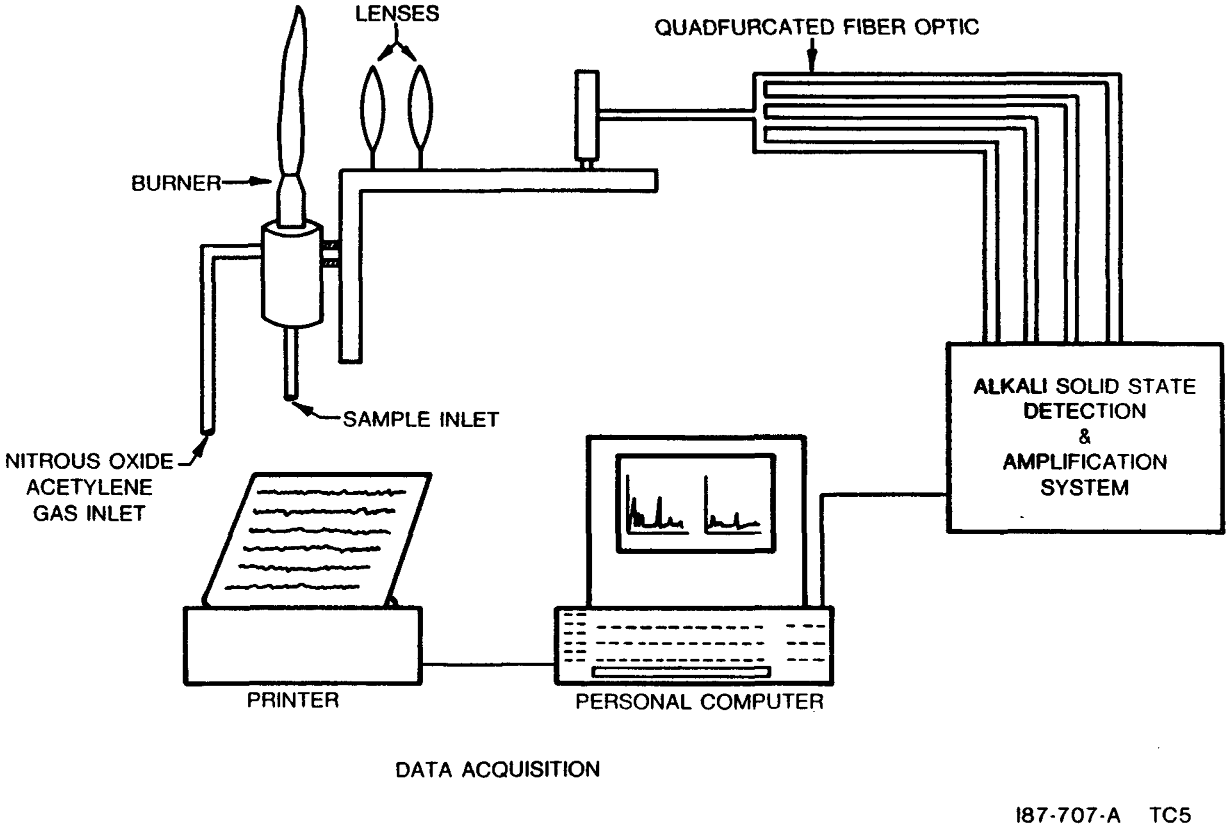

Figure 8. METC Alkali Fiber Optic Spectrometer

been performed to determine if a stainless-steel sampling line captures vapor-phase alkali. From the experiments, it appears that stainless steel has a considerable affinity for vapor. The sampling system of the METC FOAM that is being used at ANL has been reconfigured. It now minimizes the contact time between the gas and any stainless steel in the sampling line. In addition, an activated-bauxite sorber-bed monitor is being designed to estimate actual average levels of vapor alkali in PFBC exhausts independent of the measurements from the METC FOAM. This measurement does not use stainless steel sampling lines.

Particulate control technology that is under investigation for PFBC applications includes electrostatic precipitators (ESPs), screenless granular-bed filters (GBFs), and ceramic cross-flow filters (CXFs). Work at the NYU subpilot-scale PFBC facility (Figure 9) consisted of several operating test periods to test these devices.

Significant improvements have been made in the manufacturing of CXFs (Figure 10). These improvements have been structural design changes and optimized firing cycles that have dramatically improved the strength of each filter element. The design changes were made after the stresses in a CXF were modeled extensively with a finite element computer program. With earlier

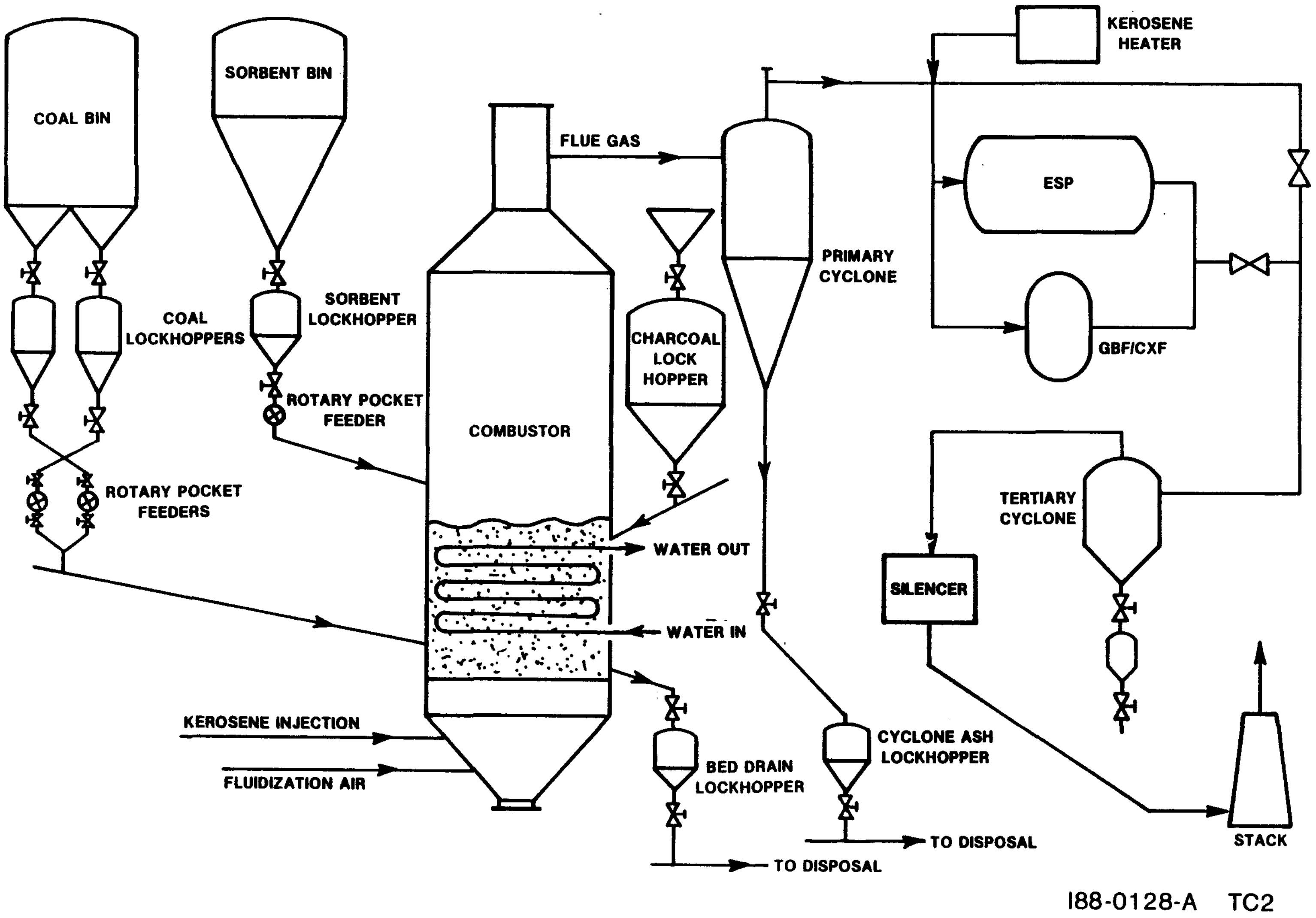

Figure 9. Pressurized Fluidized-Bed Combustion System at New York University

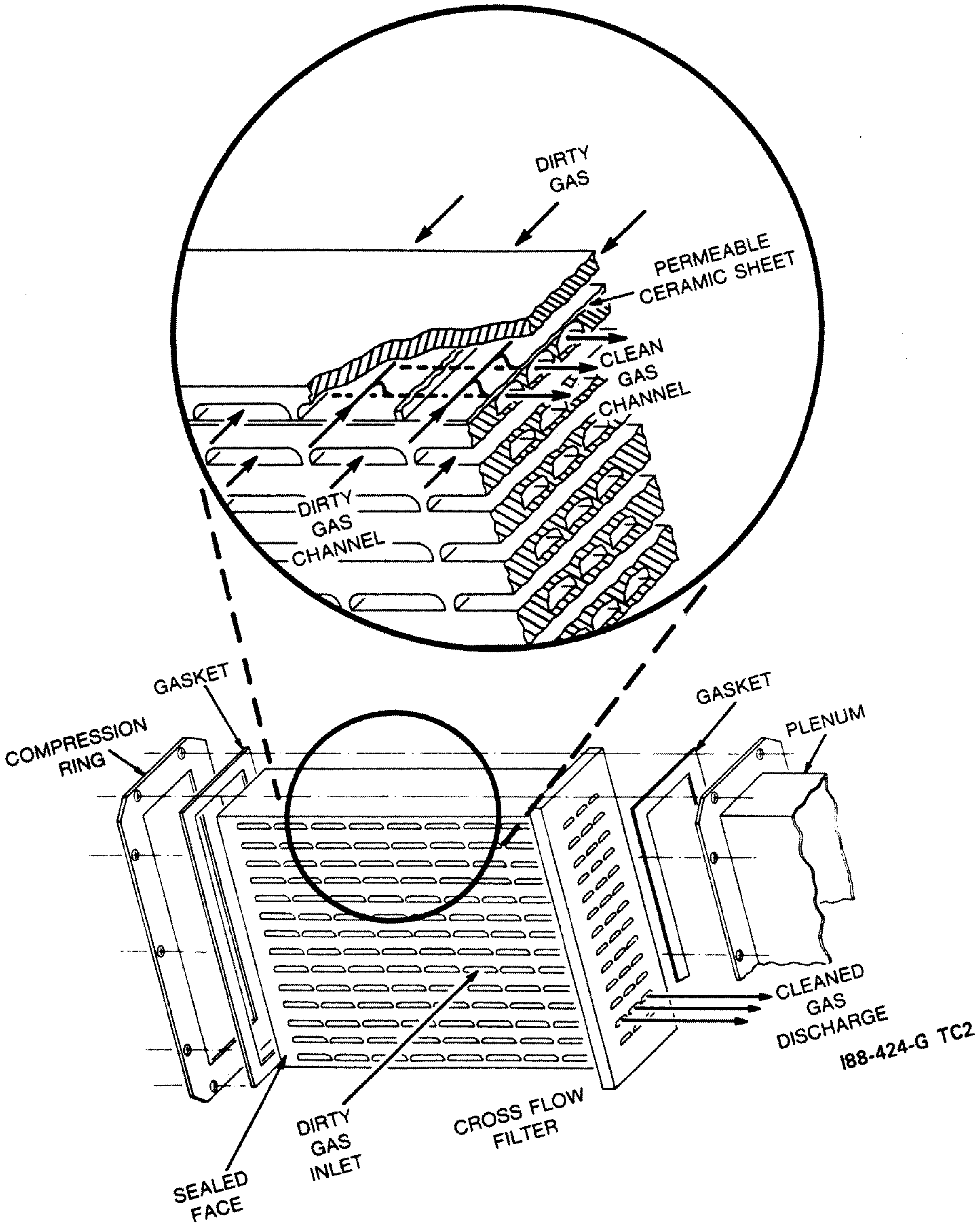

Figure 10. Cross-Flow Filter

filters, a pressure of approximately 150 psig caused the filters to separate where each layer was bonded to the next layer. The new filters have been made with a new mid-rib design, which is shown in Figure 11. These filters have exhibited a "burst" pressure of more than 230 psig, which indicates the general level of increased strength.

To confirm the improved reliability of these filters, the construction and shakedown of a HTHP test loop was initiated. This facility will simultaneously evaluate eight full-scale filters by injecting PFBC dust into a 150 psig/1,500°F natural gas-fired exhaust stream. It is anticipated that the filter facility will complete 200 operating hours in early 1988.

A contract was awarded in 1987 that includes long-term durability testing (2,000 hours) of the CXF filter. The testing was conducted under simulated PFBC conditions. Two 12-inch by 12-inch by 4-inch cross-flow filter elements will be tested to assess the durability of the components that are used to construct the cross-flow filter, as well as other system components such as pulse nozzles.

GBFs are a promising approach for controlling the particles from the HTHP exhausts of PFBC systems. The screenless GBF is shown in Figure 12. This filter uses either 2- or 3-millimeter (mm) alumina oxide granules to remove particles. The granules are circulated from the top of the filter down through a conical section of the filter module. This circulation and cleaning of the ash

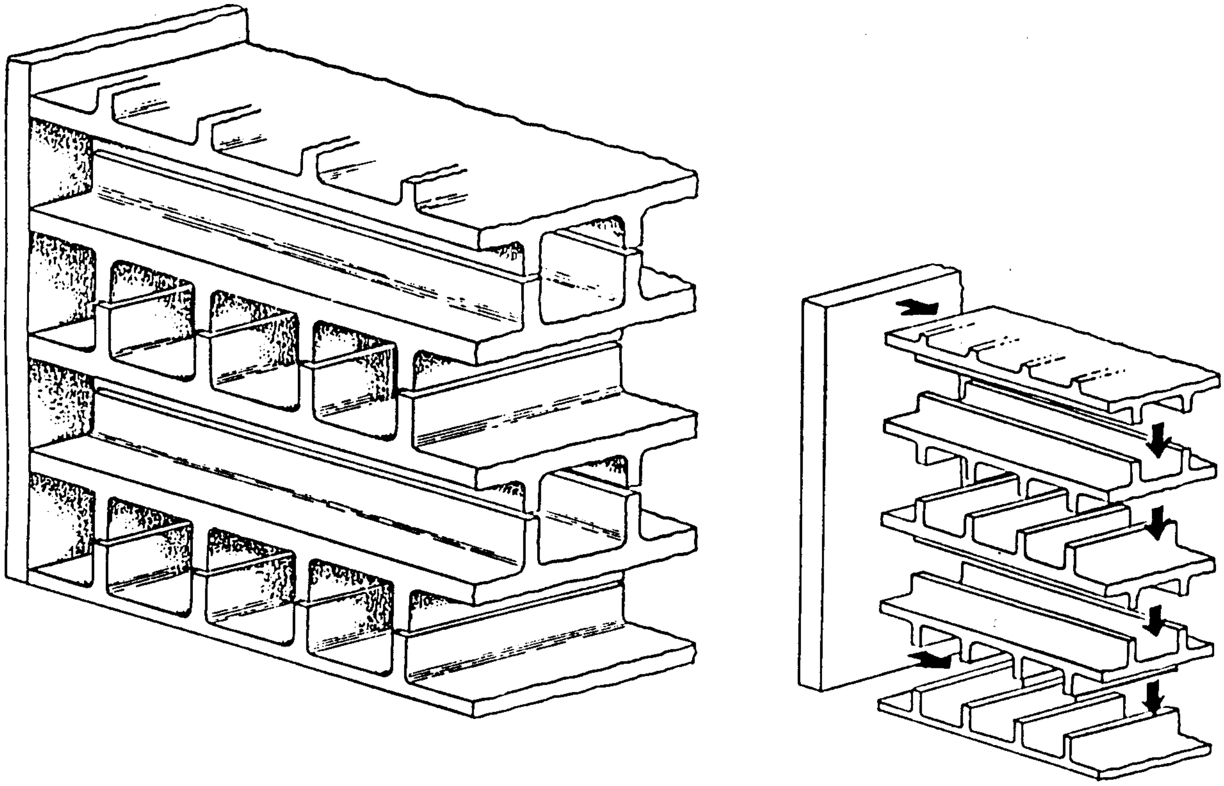

Figure 11. "Mid-Rib Bond" Concept

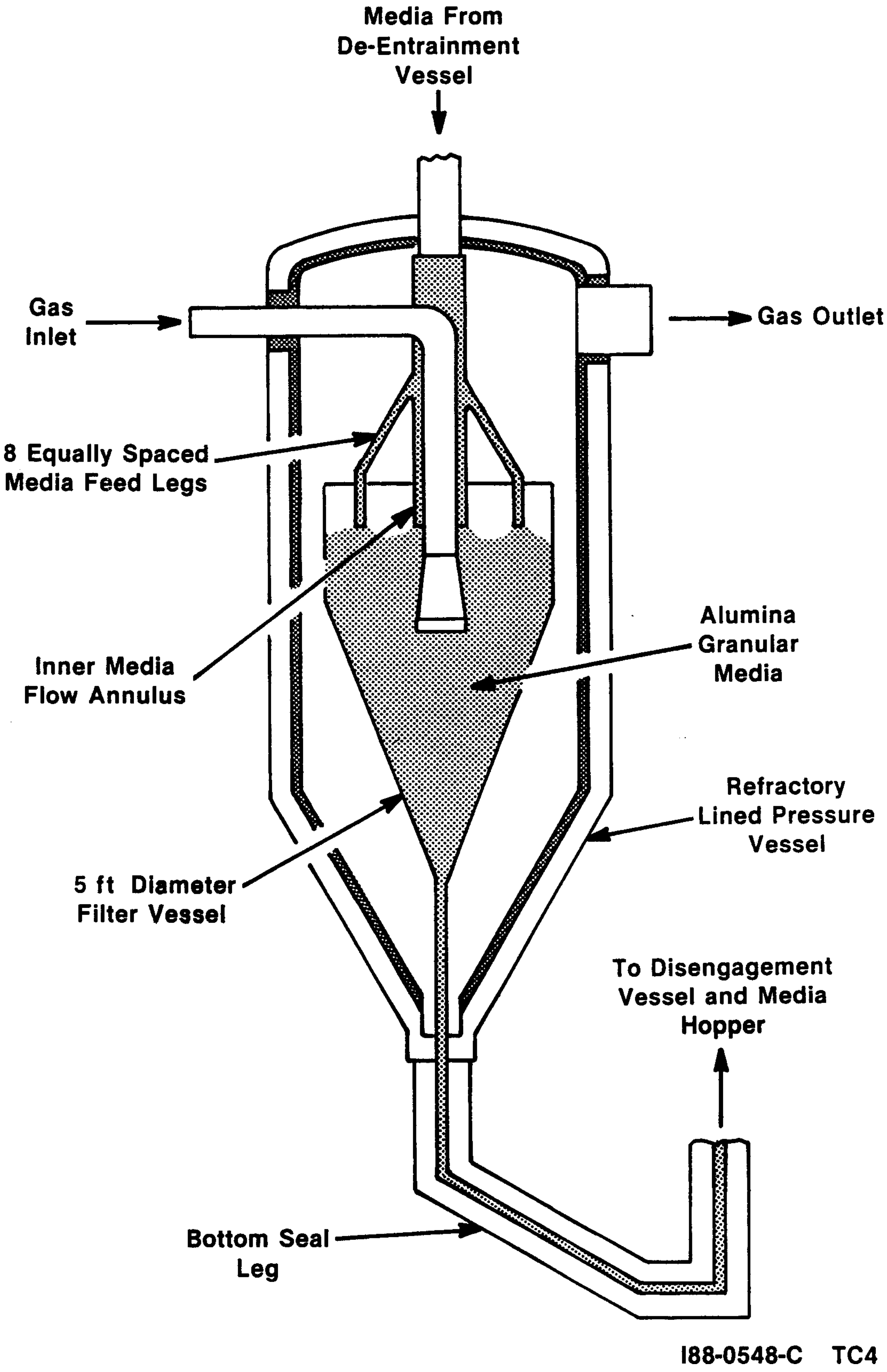

Figure 12. Screenless Granular-Bed Filter

from the granules is accomplished using a lift-pipe that entrains the granules up to the top of the filter system. A small slipstream is used to direct the particles that are knocked off in the lift-pipe into a low-temperature bag filter for final disposal of the PFBC ash.

The evaluation of the life-critical components of the screenless GBF was completed. This 500-hour evaluation period was conducted at Combustion Power Company's (CPC's) Menlo Park, California, facility before the NYU tests. Generally, several areas of high wear were observed in specific locations of the refractory-lined lift-pipe. Lift-pipe sections that were lined with silicon carbide were fabricated to resolve this problem. In addition, the filter was operated in an artificial pressure balance mode to improve the seal-leg arrangement. The lift-pipe and ancillary equipment were dismantled and shipped to NYU's PFBC facility in Westbury, New York. The results of the evaluation will be completed in early 1988.

HTHP ESPs have been proposed for removing the particulate in a PFBC exhaust. A project with Research Cottrell was initiated to determine the economics and feasibility of operating an ESP in this type of environment. The objectives were to evaluate the voltage and power requirements (the amount of current consumed) at realistic temperature, pressure, and gas conditions of a PFBC system to sufficiently collect particles to protect the expander turbine.

The evaluation of the HTHP ESP on the NYU PFBC was concluded in mid-FY 87. Figure 13 shows the installed ESP. The principle reason for terminating the tests was the inability to get sufficient voltage into the ESP. Since high

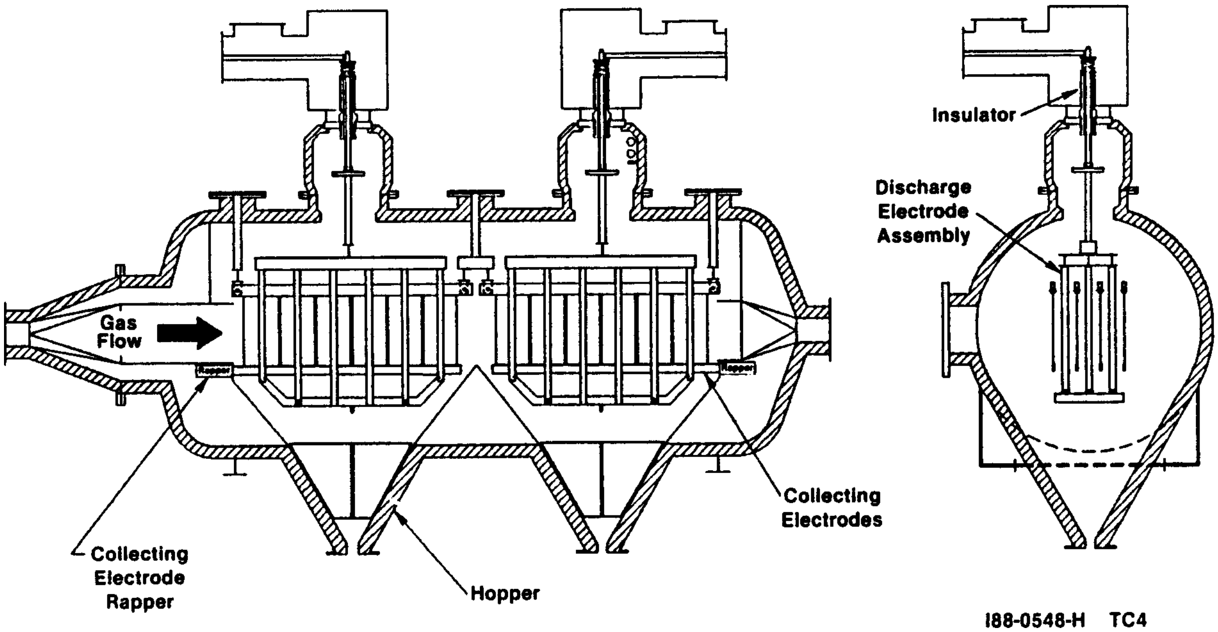

Figure 13. High-Temperature, High-Pressure Electrostatic Precipitator Tested at New York University

voltages could not be maintained on the electrodes of the ESP, the test objectives could not be met. Sufficient voltage could not be reached because the ceramic insulators that were used to feed the high-voltage power into the ESP pressure vessel failed several times. A failure analysis of the ceramic insulators was performed. The final report is being reviewed.

Finally, a novel hot nested-fiber filter (NFF) concept is also being developed by Battelle Columbus to remove particulates for PFBC applications. The NFF concept is based on a system of nested fibers made from an appropriate alloy. It operates at high velocity and with low pressure drop. Analysis of preliminary data indicates a 99.5-percent particle removal efficiency.

4.3 Gas Stream Cleanup for the Direct Coal-Fueled Turbine System

DCFT systems are in the initial stage of development and their contaminant control requirements and operating regimes have not been firmly established (Table 2). GSC researchers are closely following the development of the new DCFT systems in order to identify cleanup requirements. Because of the extremely high temperatures of DCFT systems (greater than 2,000°F), it is likely that novel cleanup concepts will be required. Cleanup concepts that are potentially feasible should first be identified and tested for effectiveness.

An initial study of particulate control for a DCFT system was completed in 1987. The objective of this study was to assess the potential of six

Table 2. Conditions and Cleanup Goals of the Direct Coal-Fired Turbine System

Temperature (°F)	1,800-2,250
Pressure (psig)	120-500
Uncontrolled Particulate Loading (g/scf)[a]	Undefined
Outlet Particulate Loading (ppmw)[b]	1 > 5 μm
Sulfur	Lower Than NSPS[c] Limits
Alkali	TBD[d]
Ammonia (Nitrogen)	*
Halogen Compounds (HCl, etc.)	*

[a] These are nominal loadings after one stage of cyclones; [b] At the outlet of the particulate control device; [c] New Source Performance Standards; [d] To Be Determined; * Controlled without hot gas cleanup.

particulate control devices for use in DCFT applications. The six particulate control devices were an ESP, a CXF filter, a screenless GBF, a ceramic bag filter, advanced cyclones, and acoustic agglomeration.

Problems with the construction materials at high temperatures appears to be the major technical limitation in using these particle control devices for DCFT applications. Contracts were awarded in response to an "Integrated Low-Emission Cleanup" solicitation that was aimed at developing high-temperature contaminant control devices for DCFT applications.

Westinghouse will study two desulfurizer configurations (Figures 14 and 15): an integrated, fine-particle entrained-flow reactor and a fluidized-bed particle reactor. Both of these systems have CXF filters to clean the process gases from DCFT systems. Cottrell-Environmental Sciences will study particle control in DCFT systems by using an electrostatic agglomeration technique followed by a high-efficiency cyclone located downstream. Sulfur will be controlled by injecting sorbent near the coal combustion discharge zone. Helipump Corporation will apply an innovative, solid-state technology to simultaneously remove sulfur, gaseous nitrogen compounds, and trace molten species from hot, pressurized combustion gas streams.

Westinghouse has evaluated the performance of calcium-based sorbents to control sulfur in a DCFT system. Laboratory-scale tests were performed at temperatures up to 2,200°F and pressures up to 300 psia using various particle sizes of dolomite and limestone. Results will be used to determine the "optimum" sulfur sorbent for DCFT applications.

Overall, both Westinghouse desulfurizer concepts can be effective in DCFTs if the correct calcium-based sorbent is selected and if applicable design and operating conditions are identified. Both concepts have limitations and key development requirements. Site- and fuel-specific engineering assessments are required to select the best concept for a given combustor system.

Because of the high temperatures in DCFTs, alkali may be a problem. Several projects in the area of alkali chemistry should directly affect our understanding of DCFTs. A coal reactor has been successfully aligned with a molecular beam mass spectrometer at Midwest Research Institute. It allows direct measurement of alkali species as they evolve from coal particles. This work is revealing valuable information on the species that evolve from the coal particle; the kind of species that evolve from the coal particle depend on the operating conditions (temperature, pressure, oxidizing or reducing environment) and the coal type. The low-rank coals are far more likely to release vapor alkali species, although it appears that the vapor form is short lived and is rapidly converted to a fume (probably alkali sulfate).

The University of California is studying the interaction of sodium and sulfur in flames by using novel analytical techniques. Results from this investigation will help scientists understand how sulfur and sodium combine to form corrosive compounds.

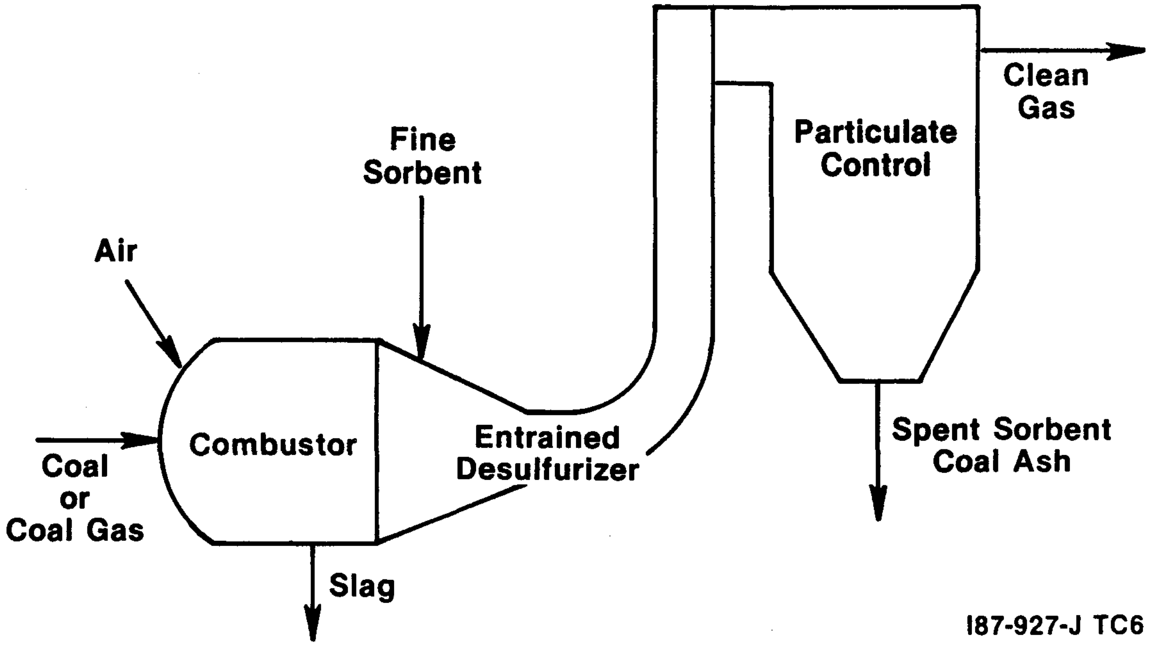

Figure 14. Westinghouse Concept for Entrained-Flow Desulfurization

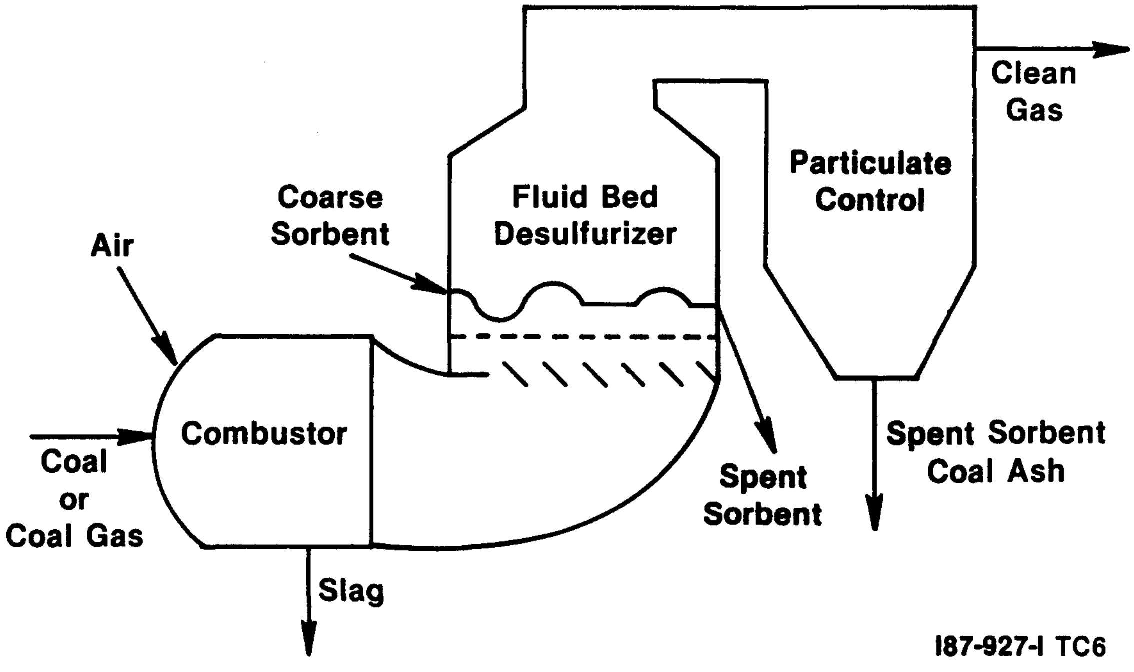

Figure 15. Westinghouse Concept for Fluidized-Bed Desulfurization

A project was completed at the University of Arizona that evaluated the effect of temperature on the distribution of alkali on large and small particles. Of particular importance, they identified the temperature quench that is required for "freezing out" the alkali sulfate fume into a solid, capturable form. This manipulation of the temperature is useful for high vapor-phase, alkali-producing coals, such as lignites, but appears to have little benefit for high-rank coals that release very little alkali in a vapor form.

Researchers at the University of Arizona also completed investigating the effect of koalin and bauxite additives on the removal of alkali fume from the flue gas of an entrained-flow downside combustor. The work under oxidizing conditions involved the testing of two coals (a Beulah lignite and an Upper Freeport bituminous coal), both with and without a quench, using both additives. Results with the Beulah lignite with quench indicated that the koalin additive decreases by one-half the sodium and potassium appearing in the small particles in the flue gas. Removal of the alkali occurred rapidly. The bauxite had no beneficial effect because of, in part, its larger particle size. Results for the Upper Freeport coal (a high-ash coal that has a high iron content) are inconclusive because of the slagging problems at or above its fusion temperature. These results indicate that, under selected coal combustion conditions, koalin clays may be used to reduce the level of vapor phase alkali.

4.4 Gas Stream Cleanup for the Integrated Gasification Combined-Cycle System

Gas stream cleanup for IGCC systems requires control of sulfur compounds, nitrogen compounds, particles, and, in some cases, alkali compounds (Table 3). In all types of IGCC systems, sulfur control concepts include removing sulfur in the gasifier by using calcium-based sorbents, and removing sulfur external to the gasifier by using regenerable, mixed-metal oxide sorbents, such as zinc ferrite.

Since removal technologies are developmental, the actual tolerance target levels that are used for various commercial applications are likely to be a compromise between long equipment life and hard-to-attain standards. Also, material enhancements that permit minimal gas cleanup, such as special turbines, may be developed simultaneously with cleanup technologies. As a result, actual cleanup requirements may be somewhat less stringent.

Before 1980, iron oxides had been identified as sulfur sorbents that could reduce the sulfur level of a coal-derived gas to limits set under the New Source Performance Standards (NSPS). However, removing sulfur to levels that are significantly lower than NSPS limits is beneficial for IGCC systems. The longevity of turbine components might be improved if sulfur-induced corrosion could be considerably reduced. In the presence of sulfur, alkalis (sodium and potassium) react under oxidizing conditions to produce sulfates, which easily adhere to metal surfaces. Research performed at METC showed that zinc ferrite (a spinel-type iron and zinc compound) has a higher sulfur-adsorption capability than iron oxide and that it is also easily regenerable.

Table 3. Conditions and Cleanup Goals for the Integrated Gasification Combined-Cycle System

Temperature (°F)	1,000-1,800
Pressure (psig)	120-1,500
Uncontrolled Particulate Loading (ppmw)[a]	200-3,000
Outlet Particulate Loading (ppmw)[b]	1 > 5 μm
Sulfur	Lower Than NSPS Limits for SO_2
Alkali	< 0.024 ppmw
Ammonia (Nitrogen)	Lower Than NSPS Limits for NO_x Following Combustion
Halogen Compounds (HCl, etc.)	*

[a] These are nominal loadings after one stage of cyclones; [b] At the outlet of the particulate control device; * Controlled without hot gas cleanup.

Several projects are underway to support zinc ferrite development. These projects include investigations into improvements that may be required for large-scale applications. Specific areas of investigation have been identified as having particular relevance to the eventual commercial use of this desulfurization method. One of these areas is the work to improve sorbent durability. Probably the greatest uncertainty in the development of the high-temperature desulfurization concept is the durability of the sorbent over many adsorption/regeneration cycles. Not only must the desulfurization sorbent retain its adsorption capacity, but it must also retain its strength and not disintegrate. Although it depends on the economics involved, durability on the order of 100 cycles is thought to be necessary. To establish this durability, AMAX Extractive Research and Development, Inc. (a company with broad experience in extractive metallurgy) is investigating ways to improve the basic zinc ferrite sorbent and ways to test candidate sorbents over many sulfidation/regeneration cycles in a laboratory-scale system.

Zinc ferrite extrudates that were used in past METC work established a base case for durability. AMAX is testing several potential improvements such as modified chemical composition, new agglomerating and hardening procedures, and optimal agglomerate size and shape. AMAX has made considerable progress in developing improved formulations of zinc ferrite. The "best" AMAX sorbent has shown double the physical crush strength and twice the sulfur-bearing capacity of the initial METC sorbent. During the desulfurization testing, the AMAX sorbent has shown a better capacity for retaining its intial surface area. The AMAX sorbent also showed improved resistance to fines attrition during desulfurization. Work is being continued on the preparation, characterization, and testing of the newly formulated zinc-ferrite sorbent samples.

Several important steps were taken toward zinc ferrite commercialization in 1987. General Electric Company (GE) completed the design of a moving-bed, zinc ferrite system for POC testing using the fixed-bed gasification facility in Schenectady, New York. GE was awarded a contract to install and test the system that is shown in Figure 16.

A modification to METC's fluidized-bed gasifier was initiated to possibly add a full-flow cleanup system to the facility. As a minimum, the hot gas cleanup train should include full-flow particulate and sulfur control concepts. It is expected that the facility will be ready for testing at the end of 1988.

The higher temperature of the fluidized-bed and entrained-flow gasification IGCC systems demand high-temperature sorbents. Novel desulfurization sorbents have the potential for higher temperature applications, lower sulfur level in the cleaned gas, and simpler offgas treatment schemes than the zinc-ferrite desulfurization process. The Institute of Gas Technology (IGT) is developing a high-temperature desulfurization sorbent that can produce elemental sulfur directly during regeneration. A sorbent with these characteristics would greatly simplify and reduce the cost for treatment of regeneration offgases. Laboratory tests using a mixed metal-oxide sorbent (cobalt titanate/zinc oxide) showed that about 35 percent of the sulfur in the regeneration offgases was elemental sulfur. Additional laboratory-scale tests are being conducted to confirm the performance of the sorbent before bench-scale testing using coal-derived gas from IGT's fluidized-bed gasifier.

The Massachusetts Institute of Technology recently completed laboratory-scale studies to develop sorbents that can remove sulfur in coal-derived gas streams at temperatures up to 1,500°F. These sorbents contain various combinations of mixed metal oxides such as zinc oxide, aluminum oxide, copper oxide, iron oxide (ferrite), titanium oxide, and molybdenum oxide. Overall sorbent evaluation/recommendations are as follows:

- The ternary oxide sorbent $(CuO)_3$-Fe_2O_3-Al_2O_3 clearly exhibits the best overall characteristics for hot gas cleanup applications up to 1,500°F.

- The addition of TiO_2 into ZnO (or $ZnFe_2O_4$) suppresses ZnO reduction during sulfidation at 1,200°F and enhances sorbent regeneration (without sulfate formation) at 1,200° to 1,300°F. The tradeoff is a reduction of the sulfur capacity of the sorbent.

Several promising sorbent formulations (CuO-Al_2O_3, ZnO-TiO_2, Cu-Fe_2O_3-Al_2O_3) were identified and will be tested by Research Triangle Institute (RTI) in a pressurized bench-scale reactor using simulated coal-derived gas. RTI's system is shown in Figure 17.

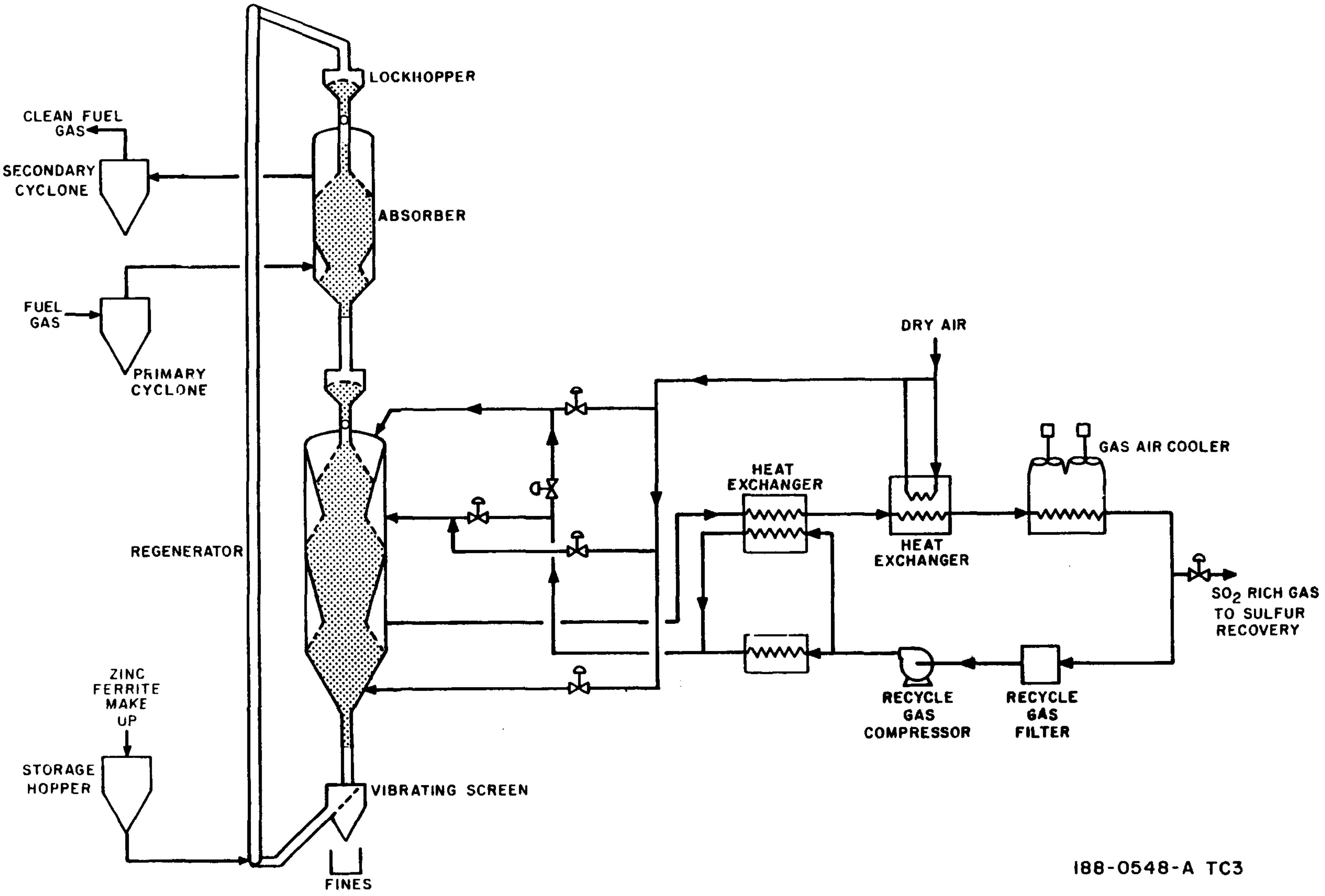

Figure 16. Moving-Bed Zinc Ferrite System

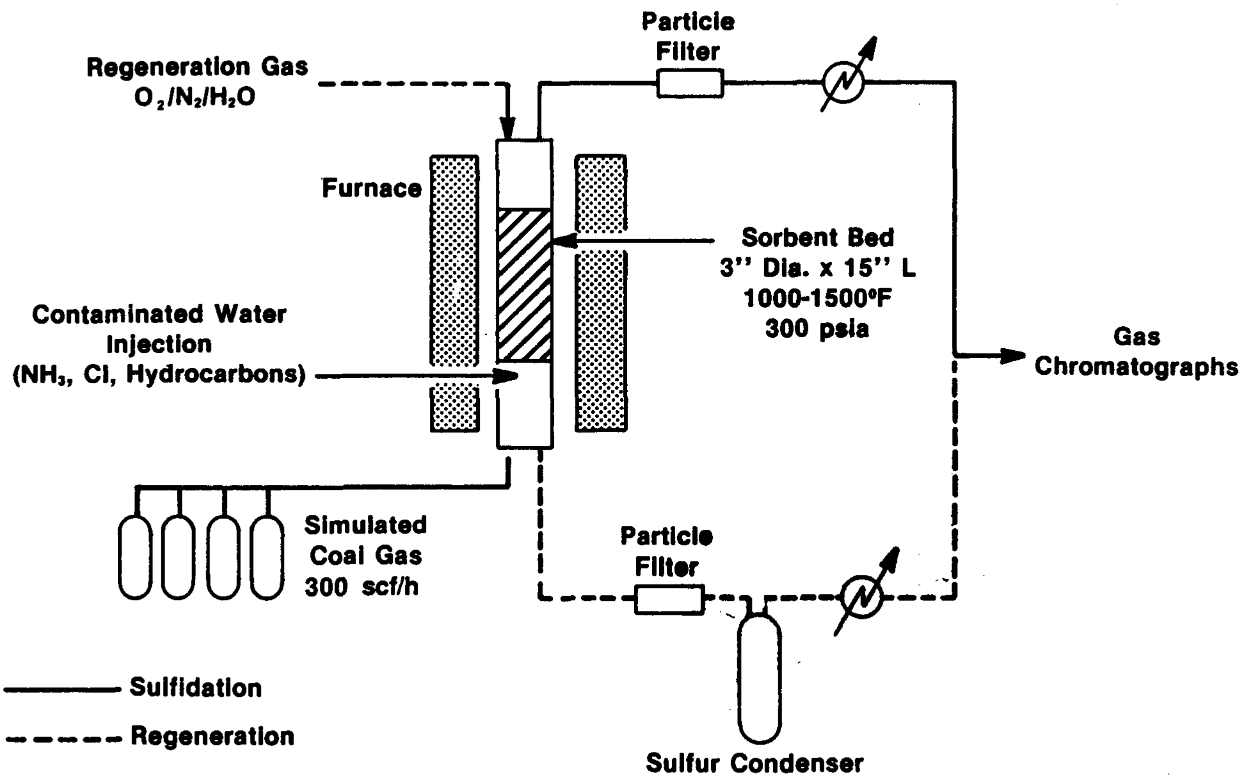

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Figure 17. RTI's Bench-Scale Desulfurization Reactor System

The major conclusions of RTI's work to date are as follows:

- H_2S < 1 part per million by volume (ppmv) was achievable when zinc copper ferrite was used as the sorbent.
- Zinc titanate sorbent is thermally stable up to 1,380°F with negligible zinc evaporation.
- Sorbent utilization is a weak function of temperature.
- 40- to 50-percent utilization is possible at 150 to 300 psia when the reactor's height to diameter ratio is 5:1, and superficial velocity is 2 to 60 mm/s.

The final determination of which processes will be usable in sulfur removal systems will depend on economics. Gilbert/Commonwealth completed a study that provides an engineering cost and economic analysis. The study compared commercial-scale designs for the zinc ferrite system, the IGT mixed-metal process, and also Battelle-Pacific Northwest Laboratories' (BPNLs') solid-supported molten salt process. The most economical desulfurization design for MCFC and IGCC systems was the zinc ferrite system used with a Kellogg-Rust-Westinghouse (KRW) gasifier.

TRW, Inc. (TRW) (Figure 18) has successfully completed testing and analyzing the range of applicability of a unique material system for hot gas cleanup. Preliminary tests conducted by TRW indicated that fibrous carbon

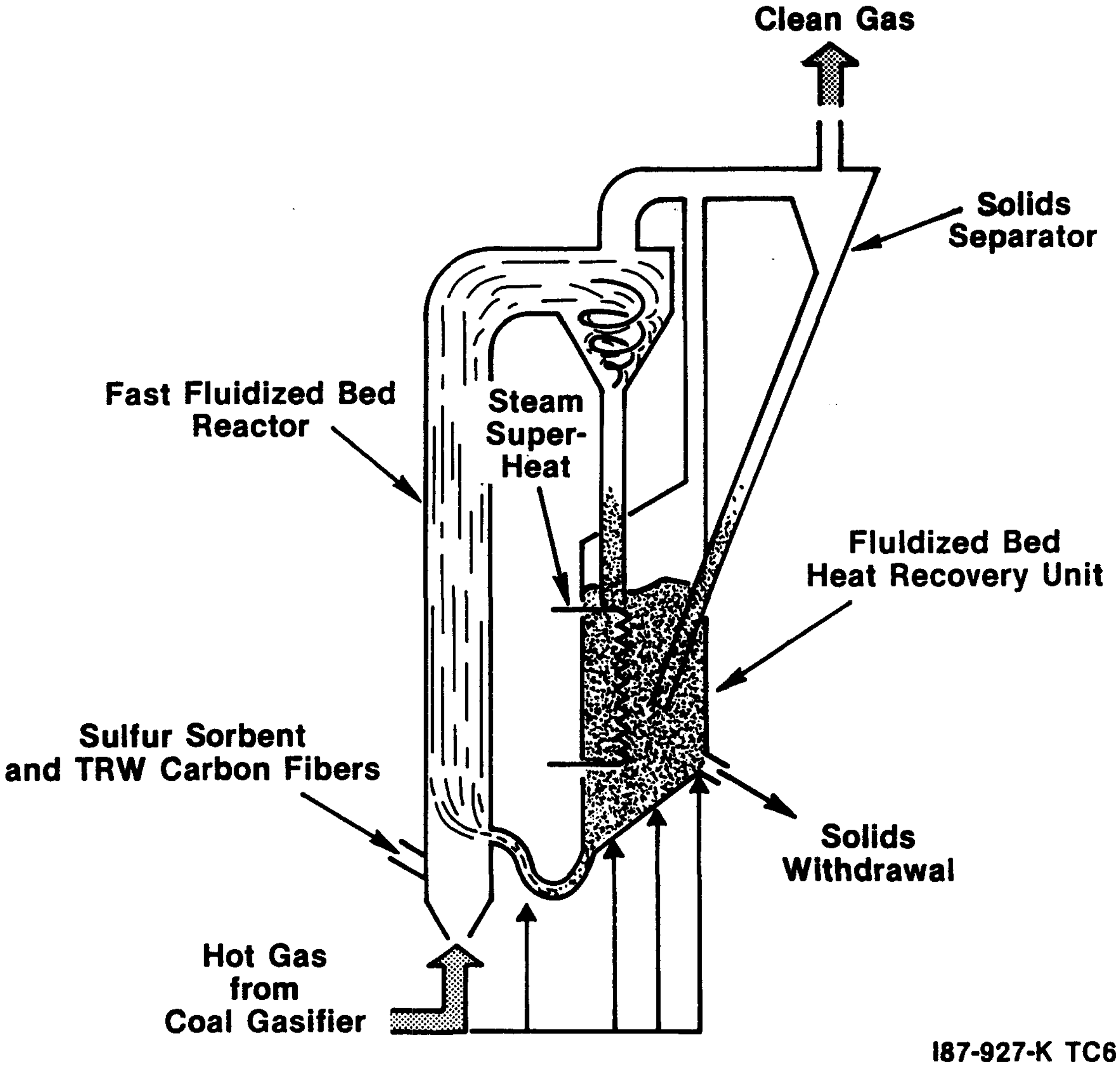

Figure 18. TRW's Hot-Gas Cleanup Process

will fluidize ultrafine sulfur sorbents, which would otherwise be too cohesive to function effectively in hot gas environments. The ultrafine sorbents would have an increased surface area and should prove to be highly effective for sulfur removal. The combination of fibrous carbon and ultrafine sorbent is proposed to simultaneously remove the sulfur and the fine particulates in the hot gas stream; this would be an advantage over current systems that require separate filtration devices. The material system was tested with respect to fluid dynamics, sulfur capture, and fiber stability behavior. The experimental program was augmented by incorporating an engineering and economic evaluation of the concept into an IGCC system. This process demonstrated the following:

- Acceptable cold-flow fluidization properties of cohesive sorbents when less than 20-weight percent of TRW carbon was added.
- 75- to 80-percent theoretical sorbent utilization (1.20 Ca/S mole ratio) at 90 percent sulfur conversion. This was demonstrated with four out of five selected sorbents.
- A weight loss of less than 10 percent of TRW carbon fibers per minute at less than 1,890°F.
- Improved thermal efficiency over air-blown and oxygen-blown systems using existing gas cleanup technologies.

The allowable level of alkali metals in the expansion gases for turbine components in IGCC systems is derived from the standards that were established for oil-fired turbines (0.02 ppmv). Alkali appears to be condensed on particles at temperatures below about 1,200 to 1,400°F. This permits alkali to be controlled in fuel gas by removing particles to sufficiently low levels. The quantity of particles that is elutriated from fixed-bed gasifiers is relatively minor and can be easily controlled by state-of-the-art cyclone separators. Above 1,400°F, alkali may need to be removed in alkali gettering reactors. This limit is designed to indicate the maximum allowable alkali content in a process stream that would prohibit alkali-sulfate-induced corrosion and would permit acceptable component longevity. It is believed that the amount of alkali in the vapor phase is correlatable to the amount of corrosive attack in a turbine system.

Studies are being performed on the mechanisms of fundamental release and subsequent capture of alkali species. It is particularly important to determine the concentration of alkali in a coal process stream in order to determine how much will have to be removed in order to meet component longevity standards. Therefore, accurate measurement techniques must be developed, as well as a better understanding of the factors that govern the release of alkali from the coal. The alkali species involved must also be identified.

An additional contaminant in IGCC systems that use fixed-bed gasifiers is fuel-bound nitrogen, primarily ammonia. Ammonia will form nitrogen oxides during combustion in the combustor-gas turbine. Steam injection, staged combustion, or catalytic decomposition of ammonia are potential ways to control nitrogen oxides.

SRI International (SRI) is investigating catalytic decomposition to control ammonia. Three non-metal catalysts were evaluated for their ammonia decomposition activities in simulated coal gas environments. Tests with MoS_2-based catalysts indicated that although their activity was low at 1,022°F, it was higher at 1,450°F. Nearly 70 percent of the feed gas ammonia was decomposed. This catalyst required the presence of H_2S (> 1,000 ppmv) to retain its stoichiometry. Two doped zinc-ferrite sorbents were also tested. Although a NiO-doped zinc-ferrite sorbent exhibited a small activity at 1,022°F, its activity decreased with time. CuO-doped zinc ferrite did not exhibit any activity at 1,022°F. Of all the catalysts listed in this program, only promoted nickel catalysts have shown high activities for ammonia decomposition. A parametric run will be performed with this catalyst. The effects of total pressure, concentration of NH_3 and H_2S, temperature, and space velocity will be examined.

Acurex is investigating two-stage combustion to reduce NO_x production. Fuel gas is combusted under rich conditions in the first stage to convert ammonia to hydrogen and molecular nitrogen. Sufficient air is then added to the second stage to complete the combustion and raise the temperature to that required for the gas turbine inlet. Acurex will also test a combined staged combustion and catalytic decomposition method to control ammonia.

BPNL is testing ammonia removal by chemisorption on various zeolite catalysts. Results to date show that NH_3 can be adsorbed on zeolites at high temperatures. Mordenite was the most effective zeolite for adsorbing NH_3 at 1,022°F and 147 psig pressure. Water vapor in the gas had a dramatic negative effect on the adsorption of NH_3. Most zeolites have a high affinity for water. Apparently the water competes for the same sites on the zeolite that chemisorb the NH_3. Dealuminating H-mordenite by treating it with HCl significantly improved its performance with water vapor in the gas. Dealuminating H-mordenite makes it more hydrophobic.

Some improvements can likely be made in zeolite performance for NH_3 removal, but it is unlikely they would be of the magnitude that is necessary to make the process practical for hot coal gas cleanup systems. Using zeolites to remove NH_3 at high temperatures might be used in applications where the gas is dry or fairly dry (< 10 vol-% water vapor) and the NH_3 content is low.

In fluidized-bed and entrained-flow IGCC systems, sufficient particulate removal does not appear to be possible with state-of-the-art cyclone separators because of the high level of elutriation of fine ash and char particles. Advanced, high-efficiency particulate removal devices are being developed for these HTHP operating conditions.

The CXF filter is also being investigated for particle control in gasification environments. Work has continued under the Westinghouse contract, "Evaluation of Ceramic Cross-Flow Filter on a Bench-Scale Coal Gasifier." The contract has been modified to allow a multiple filter element test. This multiple element filter test will be conducted at KRW using a simulated PFBC test passage. This test passage is a rebuilt test passage that was used in the early 1980s to evaluate particle control devices and is referred to as Test Passage 5. This test will simultaneously generate data on eight full-sized filter elements. The 200-hour operating period will also be the first time that more than one filter per gas plenum has been evaluated. These tests will be conducted in late 1987, and the final report for this contract will be submitted by early 1988. The need for a multiple filter test was established in early 1987 when Westinghouse tried to evaluate the full-scale filters that were supplied by both Coors Ceramic Company and General Telephone and Electronics (GTE). Each filter was evaluated singly, which required approximately two weeks per filter element. It became obvious that using the Westinghouse Research and Development (R&D) laboratory to determine the statistical reliability of the CXF elements was not cost effective. In addition, one needs multiple element tests to start to understand such things as manifolding.

4.5 Gas Stream Cleanup for the Gasification/Fuel Cell System

Cleanup requirements for MCFC and SOFC systems are generally more stringent than those for gas turbine applications. Previous studies showed that soot, hydrocarbons, particulates, halogen, and certain trace elements are potentially deleterious to MCFC performance and life. It appears now that the uncombusted carbon and noncombustible mineral matter in the gas stream must be reduced to very low levels to ensure proper operation of an MCFC system. The porous nickel anode of the fuel cell is sensitive to plugging by high levels of particles. Zinc ferrite units are also sensitive to a high concentration of particles; thus, particles must be removed to ensure proper operation. Hydrogen sulfide and chloride can poison the electrolyte and corrode hardware. Heavy metals can also poison the electrolyte. Tars and oils can affect fuel cell operation by plugging the porous electrodes.

Preliminary tolerance limits of MCFC systems for alkalis, ammonia, hydrogen sulfide, hydrogen chloride, hydrogen fluoride, tars, soot, zinc, and arsenic have been established. Previous work has indicated that to prevent electrode and electrolyte poisoning, a MCFC system requires a fuel gas with no more than 1 ppmv of sulfur. The regenerable, mixed-metal oxide sorbents that were produced by RTI for IGCCs appear suitable for MCFC applications since they meet the 1 ppmv sulfur level. Contaminant tolerances are summarized in Table 4.

The objective of the work that was conducted at IFC was to determine the tolerance levels for halides in fuel and oxidant gas streams, and to characterize the effects of these contaminants on the performance of the coal gas-fueled MCFC system.

IFC found that the tolerance of the cell stack to halides depends on the cell design and its electrolyte inventory, the operating conditions of the stack, and the system that incorporates the stack. Using a stack operating at the conditions shown in Table 5, no halide leaves the anode and enters the cathode in the oxidant gas. Under such conditions, the tolerance level of HCl and HF is about 0.1 ppmv, based on a performance loss of 20 mV in 40,000 hr.

Table 4. Molten Carbonate Fuel Cell Contaminants, Effects, and Tolerances

Contaminant	Possible Effect	Tolerance
Sulfur (H_2S, COS)	Sulfation of Carbonate Electrolyte Deactivation of Anode Sulfation of Anode Sulfation of Hardware	1 ppmv
Ammonia	Electrolyte Compositional Changes	0.5 vol-%
Halogen Compounds (HCl, etc.)	Deactivation of Anode Electrolyte Compositional Changes	0.1 ppmv
Hg, Pb	Corrosion, Deactivation	30 ppmv; 1 ppmv
Zn	Deactivation and Plugging	15 ppmv
As	Deactivation and Plugging	1 ppmv
Hydrocarbons (Saturated, Olefin, Aromatic, Cyclic)	Soot Formation	12; 0.2; 0.5; and 5 vol-%
Particulate Loading	Blockage	10 ppmw > 1 μm (Effect of < 1 μm TBD)
Alkali	Not Identified as a Contaminant	--

The fuel and oxidant compositions that are presented in Table 5 are the same as those that were used in the experiments performed at IFC. These conditions represent the operation of an oxygen-blown Texaco gasifier. Such operation also includes reduced CO_2 pressure to extend the life of the nickel oxide cathode.

A model was used to estimate the decline in performance with time caused by the presence of halides for four cases: hydrogen chloride in the fuel and oxidant and hydrogen fluoride in the fuel and oxidant. The projected performance decay after 40,000 hr of operation as a function of halide content is shown in Figure 19. These decay levels are those only caused by the presence of halide, and do not include any decay that is caused by other sources. Other decay modes include electrolyte loss, nickel oxide cathode dissolution, current collector corrosion, cathode compaction, and anode creepage all in the absence of halides.

Table 5. Typical Molten Carbonate Fuel Cell Operating Conditions

Operating Pressure	= 1 atm
Operating Temperature	= 1,200°F
Current Density	= 172 mA/cm^2
Fuel Composition:	29.4 mole % H_2 5.5 mole % CO 17.5 mole % CO_2 47.6 mole % H_2O
Fuel Utilization (H_2 + CO)	= 85%
Oxidant Composition:	9.6 mole % O_2 7.2 mole % CO_2 64.6 mole % N_2 18.7 mole % H_2O
Oxidant Utilization (CO_2)	= 37%
Operating Time	= 40,000 hr

A wide range of sophisticated test procedures was developed at the Energy Research Corporation (ERC) to accomplish several objectives: adding and detecting various contaminants in the fuel gas, and simulating borderline stable gas compositions for use in out-of-cell thermogravimetric analysis (TGA) experiments and in-cell MCFC studies. Altogether, nine bench-scale (300 cm^2) and laboratory-scale (30 cm^2) MCFC systems were operated, providing a total of 2,800 hr of cumulatively acquired experience. The most significant results that were achieved during this program are as follows:

- Established carbon deposition critical zones for MCFC fuel gas compositions. These were established over a range of temperatures and at different total pressures of the system, as well as with different fractions of inert gas (i.e., N_2) in the fuel.

- Determined that in a normal steam-/hydrogen-containing coal fuel gas, the theoretical Boudouard soot-forming equilibrium tends to be suppressed when the fuel cell anode and hardware surfaces are wetted with a molten carbonate electrolyte (Figure 20).

- Examined typical Texaco coal gas compositions for their soot-forming tendency. Established that the TGA experiments with carbonate-wetted porous nickel anodes correlate well with the in-cell operations, which shows that no additional steam is required.

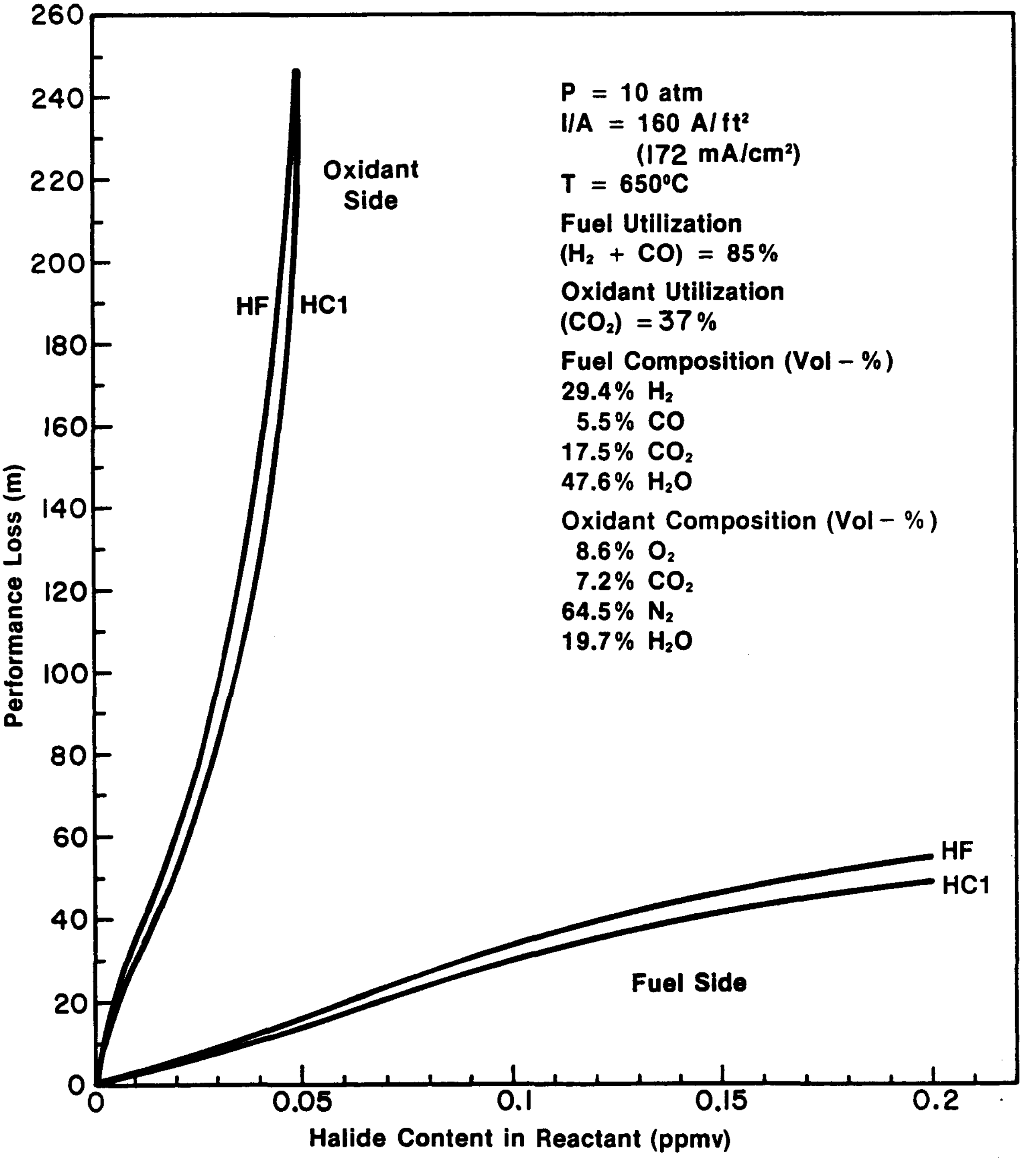

Figure 19. Predicted Performance Decay in 40,000 Hours Caused by Halides

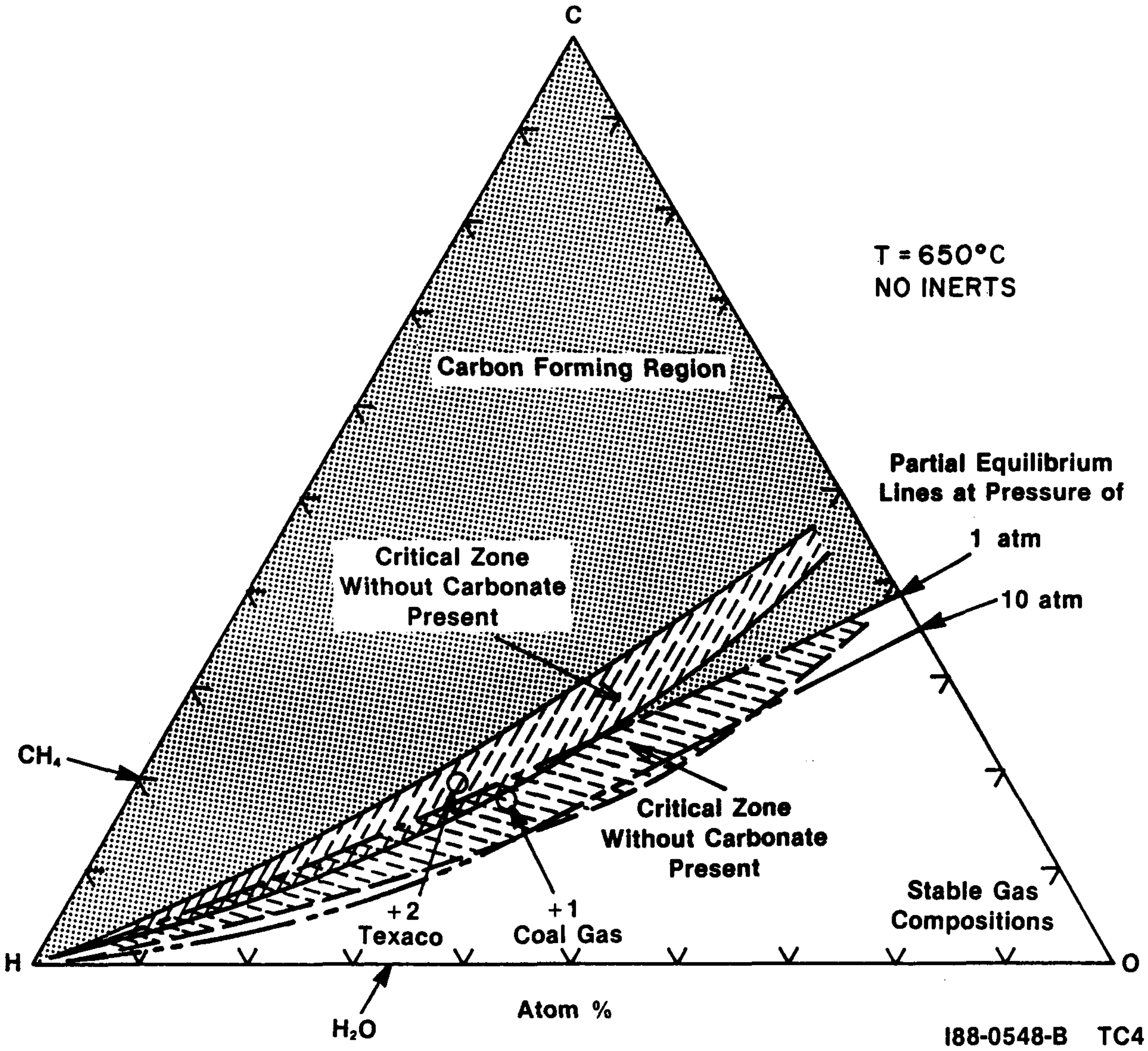

Figure 20. Carbon Formation Boundaries With and Without Carbonate Melt

- Determined by hydrodynamic modeling that typical gasifier particulates that are > 1 μm in size will rapidly separate and deposit in subsystem conduits well before the material can reach the internal anode passages. This was confirmed in a typical bench-scale cell configuration. Submicrometer particles in a high-temperature gas stream were also found to quickly form large-sized agglomerates (>> 1 μm).

- Showed that < 10 ppmw, which represents a typical gasifier dust load of > 1 μm particles, is probably a safe limit for inert particle contamination in MCFC fuel gas. This was shown through cell testing with inert $LiAlO_2$ particulates.

- Established that < 1 ppmv arsenic, when ingested by a bench-scale MCFC system can be considered to be a relatively safe short-term tolerance limit that causes little detrimental effect on the performance of the cell.

- Noted some increases in cell resistance and a decrease in performance when up to 1 vol-% ammonia was added to the fuel of a bench-scale MCFC system. Since greater than 90 percent of the ammonia was detected undecomposed in the exhaust gas, this contaminant may have been responsible for only minor cell decay. Fuel gas should probably contain less than 0.5 vol-% NH_3 to avoid possible long-term detrimental effects.

- Showed by out-of-cell TGA experiments that neither Hg- nor Pb-vapor in fuel reacts with anode surfaces that are carbonate-wetted porous nickel. However, found that fuel containing 1 ppmv of Pb-vapor can combine with dry nickel surfaces.

- Established that 0.2 vol-% acetylene, the least stable of the unsaturated hydrocarbon contaminants, can increase the tendency for soot to form on dry nickel anode surfaces in a medium-Btu, borderline-stable fuel. Other olefinic, aromatic, and cyclic contaminants at somewhat higher concentrations can equally aggravate such carbon deposition.

- Observed performance decay caused by fuel starvation as a result of inlet port plugging, but not as a result of soot formation on the carbonate-wetted nickel anodes. The anodes were observed during in-cell, bench-scale testing when approximately five volume percent toluene was added to a medium-Btu fuel.

- Estimated tolerances for the presence of zinc vapor in the fuel of the MCFC system: somewhat less than 15 ppmv when operated continuously with a 70-percent fuel utilization or < 30 ppmv with a 30-percent fuel utilization. The long-term effects of zinc accumulation in the electrolyte still need to be established, however.

A program at SRI used natural minerals and commercial sorbents to remove HCl vapor contaminants from high-temperature coal gas mixtures. Removal of HCl vapor is essential for sustained, efficient operation of MCFC systems. Sodium carbonate-based sorbents reduced the level of HCl to about 1 ppmv in coal gas streams at 995 to 1,200°F. In a laboratory-scale study of three minerals and two commercial sorbents, the total capacity of the sorbent for retaining chloride was found to depend on its active sodium content and porosity. After calcination, the mineral nahcolite had a capacity of 54 wt-% chloride because of its high sodium content and moderate porosity. Even though commercial sorbents have high surface areas, they have much lower chloride capacities because of their low sodium content. The reaction between HCl vapor and the sorbents was rapid and the initial rate was controlled by gas phase mass transfer. A bench-scale study was conducted with simulated "clean" coal gas and coal gas that contained H_2S, organic, and trace metal impurities. The bench-scale study confirmed the results of the laboratory study. H_2S was captured by the sorbents only in minor quantities and it did not interfere with the chloride removal. The trace metal impurities As and Sb were retained in significant percentages by the sorbents. A preliminary techno-economic analysis of the HCl removal process identified nahcolite as the most economic sorbent. Capital and operating costs for a 100 megawatt (MW) commercial-size unit were estimated to range from $0.0017 to $0.0030 per kilowatt (kW) hour, depending on the type of the gasifier.

No distinction has been made between the research activities for particulate control in IGCC or MCFC systems. The primary reason for this is that the tolerance of MCFC systems to particulates has not been established. Preliminary results indicate that the required cleanup for MCFC systems should be at least as stringent as those for IGCC systems.

It is expected that operating a SOFC system with coal-derived gas will require the removal of particles as well as other contaminants that affect SOFC performance. The effect of particles, sulfur compounds, chlorides, heavy metals, tars, oils, and other potential contaminants on SOFC performance needs to be assessed.

4.6 Gas Stream Cleanup for the Coal-Fueled Diesel System

An evaluation will be performed to determine the optimum gas cleanup configurations that can be used with a CFD engine. Design considerations will include the contaminant tolerances of the system, the maximum concentration that is likely to be produced, and identification of the technology needs to achieve total removal of the contaminants. This is a new area of cleanup research that is directly related to the ongoing development of diesel technology in the METC Heat Engines Program. A major procurement was issued in 1987 to investigate CFD systems by POC testing. The program includes development of integral cleanup systems.

4.7 Gas Stream Cleanup for the Mild Gasification System

The primary goal of METC's Surface Gasification Program on MG processes is to investigate and develop gasification systems that can produce multiple products from coal. These multiple products are characterized as coal-derived liquids, gases, and chars that are generated through the application of advanced processing techniques, new catalysts, advanced treatment systems, and novel product upgrading techniques.

Research efforts are being carried out to assess the status of technology development for these gasification processes. Yields and properties of the gas, char, and liquid products are being identified. The technology for upgrading and removing contaminants from the multiple products will be examined. Fuel quality requirements for use in heat engines, as feed for chemical manufacture, and in other utilization systems will also be assessed.

Researchers in METC's Surface Gasification Program have recently begun investigating MG processes. Researchers in the GSC Program are carefully monitoring the technical advancements that are being made in the MG of coal. Significant advancements are expected to be made by 1989, and cleanup for MG processes is a planned initiative in 1989. Removal of particulates, sulfur compounds, nitrogen compounds, chlorides, alkalis, and trace metals from the multiple products is expected to be required before the products can be used in an economical and environmentally safe manner.

4.8 Technology Support Studies

Technology support studies involve projects for developing instrumentation to characterize contaminants of HTHP gas streams. They also include projects to analyze the technical and economic performance of control devices in various system configurations.

As mentioned in Section 4.2, the METC FOAM was successfully tested at the Grimethorpe PFBC facility in England. A team from Ames National Laboratory installed the monitor and obtained real-time measurements of the total alkali in the process stream. Arrangements are currently being made for obtaining alkali measurements at PFBC and IGCC sites. A procurement may be initiated in 1988 to develop a sole source to manufacture and market the FOAM. The procurement will include start-up of an alkali manufacturing facility, purchase of two FOAMs for METC, development of operating manuals, and identification of potential purchasers.

A contract was awarded to SRI to study the fate of alkali species in coal conversion systems. Work under this contract will shift the emphasis of research away from the vapor phase and towards the changes and interactions that alkali species undergo. Identification of the intermediates involved in the formation of sodium/potassium sulfate species will be particularly emphasized in order to identify the optimum point at which control of this formation should be implemented. This information will be useful for controlling alkali in DCFT, PFBC, and IGCC systems.

In-house systems analysis was done to assess the implications of HTHP sulfur, nitrogen, and alkali removal devices on the overall performance of gasification and gasification-based systems. In 1987, the investigation of important systems aspects that related to hot gas cleanup included evaluating fixed-bed gasification systems that use tail gas recycle to the gasifier for sulfur disposal, as well as evaluating other novel desulfurization schemes that were under development. The Advanced System for Process Engineering (ASPEN) zinc ferrite model was enhanced and expanded where appropriate in response to new experimental results and requirements for systems studies. The ASPEN models for tail-gas treatment were finalized, incorporated into overall gasification island simulations, used for comparison with other processes, and updated based on experimental results.

Specific accomplishments in 1987 included the following:

- Completed detailed analysis of zinc ferrite modeling capability for data analysis and scale-up studies.
- Modified the ASPEN zinc ferrite model to update operating conditions and to include the capability to predict bed pressure drop.
- Analyzed the systems aspects of fixed-bed, gasifier-based gasification island systems that capture sulfur in the gasifier to dispose of regeneration tail gases. The analysis included an economic comparison of tail-gas recycle and scrubbing options.
- Completed an ASPEN simulation of various island systems. This provided a revised cost and efficiency comparison of hot versus cold cleanup systems.
- Revised cost information to include sorbent life for zinc ferrite systems and projects.
- Finished developing ASPEN models for SO_2 treatment processes. Compared the effects of these processes with those of tail-gas recycle systems on IGCC power plants.
- Finished developing an ASPEN model of the TRW process for simultaneous sulfur and particulate removal. Incorporated the model into simulations of IGCC power systems to assess performance and other effects of integration.

4.9 Calderon Project

Calderon Energy, Inc. was awarded a grant to evaluate the performance of the Calderon gasification/hot gas cleanup process at the process development unit (PDU) scale. Calderon Energy, Inc. will construct a system (Figure 21) that will remove high levels of sulfur from gas that is produced by minimally cleaned coal. In addition, Calderon has proposed to use a regenerable sorbent that produces elemental sulfur as the regeneration by-product.

The PDU will be constructed and operated for a period of no less than 6 months. It will have the capacity to gasify 24 tons of coal per day. The effectiveness and efficiency of the desulfurization will be determined, and a design and cost analysis will be performed to determine the feasibility of applying this process to a commercial-scale, 48-MW electric power plant.

A preliminary assessment of the heat and energy balance of the Calderon system has been prepared by Bechtel, Inc., and a task report has been submitted on the progress of the Task 1 activities. A material and energy balance of the system has been made and an overall design on which a cost determination can be made is nearly completed.

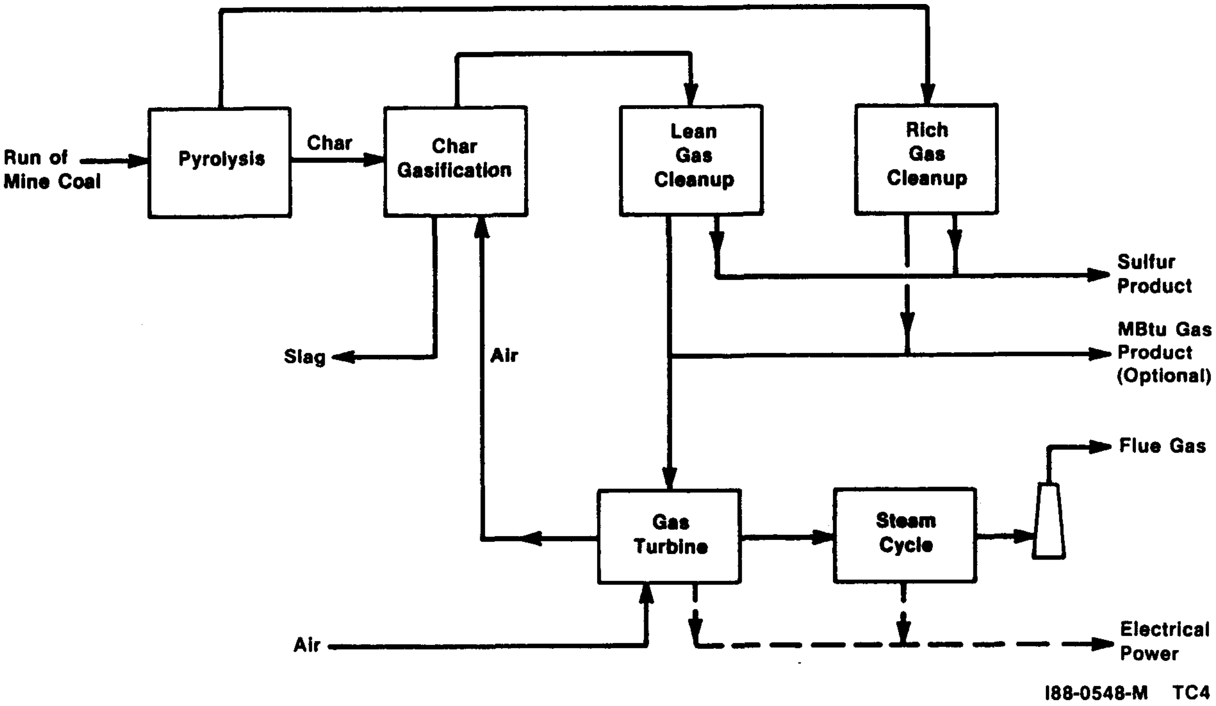

Figure 21. Calderon's Gasification Combined-Cycle Power Generation

5.0 ACRONYMS AND ABBREVIATIONS

A	Amperes
ANL	Argonne National Laboratory
ASPEN	Advanced System for Process Engineering
atm	Atmospheres
BPNL	Battelle-Pacific Northwest Laboratories
Btu	British Thermal Units
CFD	Coal-Fueled Diesel
COE	Cost of Electricity
CPC	Combustion Power Company
cm	Centimeters

CXF	Ceramic Cross-Flow
DCFT	Direct Coal-Fired Turbine or Direct Coal-Fueled Turbine
DOE	Department of Energy
ERC	Energy Research Corporation
ESP	Electrostatic Precipitator
°F	Degrees Fahrenheit
FOAM	Fiber Optic Alkali Meter
ft	Feet
GBF	Granular-Bed Filter
GE	General Electric Company
GSC	Gas Stream Cleanup
GTE	General Telephone and Electronics
hr	Hours
HTHP	High-Temperature, High-Pressure
IFC	International Fuel Cells, Inc.
IGCC	Integrated Gasification Combined-Cycle
IGT	Institute of Gas Technology
KRW	Kellogg-Rust-Westinghouse
kW	Kilowatts
mA	Milliamperes
MBtu	Thousands of British Thermal Units
MCFC	Molten-Carbonate Fuel-Cell
METC	Morgantown Energy Technology Center
MG	Mild Gasification
mm	Millimeters
MW	Megawatts

μm	Micrometer
NFF	Nested Fiber Filter
NO_x	Nitrogen Oxides
NSPS	New Source Performance Standards
NYU	New York University
PDU	Process Development Unit
PFBC	Pressurized Fluidized-Bed Combustion
ppbw	Parts per Billion by Weight
ppmw	Parts per Million by Weight
ppmv	Parts per Million by Volume
POC	Proof-of-Concept
psia	Pounds per Square Inch Absolute
psig	Pounds per Square Inch Gauge
R&D	Research and Development
RTI	Research Triangle Institute
scf/h	Standard Cubic Feet per Hour
SOFC	Solid-Oxide Fuel-Cell
SO_2	Sulfur Dioxide
SRI	SRI International
TBD	To Be Determined
TRW	TRW, Inc.
TGA	Thermogravimetric Analysis
vol-%	Volume Percent
wt-%	Weight Percent

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